Document made available under the Patent Cooperation Treaty (PCT)

International application number: PCT/US05/001891

International filing date: 21 January 2005 (21.01.2005)

Document type: Certified copy of priority document

Document details: Country/Office: US
Number: 60/573,406
Filing date: 24 May 2004 (24.05.2004)

Date of receipt at the International Bureau: 16 December 2005 (16.12.2005)

Remark: Priority document submitted or transmitted to the International Bureau in compliance with Rule 17.1(a) or (b)

1406892

THE UNITED STATES OF AMERICA

TO ALL TO WHOM THESE PRESENTS SHALL COME:

UNITED STATES DEPARTMENT OF COMMERCE

United States Patent and Trademark Office

December 05, 2005

THIS IS TO CERTIFY THAT ANNEXED HERETO IS A TRUE COPY FROM THE RECORDS OF THE UNITED STATES PATENT AND TRADEMARK OFFICE OF THOSE PAPERS OF THE BELOW IDENTIFIED PATENT APPLICATION THAT MET THE REQUIREMENTS TO BE GRANTED A FILING DATE.

APPLICATION NUMBER: ***60/573,406***
FILING DATE: ***May 24, 2004***
RELATED PCT APPLICATION NUMBER: ***PCT/US05/01891***

THE COUNTRY CODE AND NUMBER OF YOUR PRIORITY APPLICATION, TO BE USED FOR FILING ABROAD UNDER THE PARIS CONVENTION, IS ***US60/573,406***

UNITED STATES PATENT AND TRADEMARK OFFICE · DEPARTMENT OF COMMERCE

Certified by

Jon W. Dudas

Under Secretary of Commerce
for Intellectual Property
and Director of the United States
Patent and Trademark Office

13146 U.S. PTO
052404

17858 U.S. PTO
60/573406

PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR §1.53(c).

INVENTOR(S)		
Given Name (first and middle [if any])	Family Name or Surname	Residence (City and either State or Foreign Country)
Greg	Charache	East Windsor, NJ
John C.	Connolly	Clarksburg, NJ
Holger	Schlueter	Princeton, NJ

Additional inventors are being named on the 0 separately numbered sheets attached hereto

TITLE OF THE INVENTION (500 characters max)

HIGH-POWER SEMICONDUCTOR LASER

CORRESPONDENCE ADDRESS

Direct all correspondence to:

[X] Customer Number: 26161

OR

[ ] Firm *or* Individual Name					
Address					
Address					
City		State		ZIP	
Country	United States	Telephone		Fax	

ENCLOSED APPLICATION PARTS ***(check all that apply)***

[X] Specification *Number of Pages* 22 [] CD(s), Number

[X] Drawing(s) *Number of Sheets* 19 [X] Other (specify) Cover sheet (1 page)

[] Application Data Sheet. See 37 CFR 1.76.

METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT

[] Applicant Claims small entity status. See 37 CFR 1.27.

[X] A check or money order is enclosed to cover the filing fees.

[X] The Director is hereby authorized to charge filing fees or credit any overpayment to Deposit Account Number: 06-1050

[] Payment by credit card. Form PTO-2038 is attached.

FILING FEE AMOUNT ($): $160

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

[X] No.

[] Yes, the name of the U.S. Government agency and the Government contract number are:

Respectfully submitted,

Signature Mark Bellermann Date May 24, 2004

Typed Name Mark R.W. Bellermann, Reg. No. 47,419

Telephone No. (202) 783-5070

Docket No. 14564-021P01

40220813.doc

PROVISIONAL APPLICATION FOR UNITED STATES PATENT

in the name of

Greg Charache, John C. Connolly, and Holger Schlueter

for

High-Power Semiconductor Laser

Fish & Richardson P.C.
1425 K Street, N.W.
11th Floor
Washington, DC 20005-3500
Tel.: (202) 783-5070
Fax: (202) 783-2331

ATTORNEY DOCKET:

14564-021P01

High-Power Semiconductor Laser

TECHNICAL FIELD

This invention relates to semiconductor lasers, and more particularly to a high-power semiconductor laser.

BACKGROUND

High-power diode lasers are used in many different applications. The usefulness of a laser for a specific application can be characterized by the laser's output power, the spectral line width of the output light, and the spatial beam quality of the output light. The spatial beam quality can be characterized in several ways. For example, a wavelength independent characterization of the spatial beam quality is provided by the beam parameter product ("BPP"), which is defined as the product of the beam waist, ω_o, and the half far-field divergence angle of the beam, θ_o, (i.e., $BPP = \omega_o\theta_o$). As another example, a dimensionless characterization of the spatial beam quality is provided by the beam quality factor, M or Q, where, $M^2 = 1/Q = \pi\omega_o\theta_o/\lambda$, with λ being the wavelength of the output laser light.

To achieve high power output from a semiconductor laser diode, a relatively wide lateral width of the active material in the laser can be used. Such devices may be known as "wide stripe emitters," broad stripe emitters," or "multimode devices." However, when the lateral width of the active material is greater than several times the laser output wavelength, gain can occur in higher order spatial modes of the resonant cavity, which can reduce the spatial beam quality of the output laser light.

Multiple wide stripe emitters can be fabricated side-by-side on a single chip to a make an array of laser diodes. The output light of multiple individual laser diodes in an array can be combined incoherently to increase the overall output power from the chip. However, the quality of the combined output beam generally decreases with the number of individual emitters in an array.

SUMMARY

The output of a multimode laser device is partially reflected by an external reflector having a reflectivity that depends sensitively on the wavelength and direction of the laser

light. By using an appropriate wavelength- and angular-reflectivity response in the reflector, the spatial beam quality Q and the spectral line width $\Delta\lambda$ of the multimode devices can be substantially improved. At the same time, the output power of the multimode device can be increased by increasing the emitter width, the number of emitters (e.g., in an array), or the number of arrays (e.g., in a stack of arrays). Thus, high power, narrow line width, high beam quality, and therefore high brilliance devices are possible.

In a first general aspect, a light source includes a semiconductor laser diode and a narrow spectral and spatial bandwidth reflector in optical communication with respect to the semiconductor diode laser and aligned with the output beam of the diode laser, such that a portion of the light in the output beam is reflected back into the laser.

One or more of the following features can be included. For example, the reflector can be a volume diffractive grating. The light source can further include multiple laser diodes aligned with respect to the reflector such that a portion of the light from each of the laser diodes is reflected back into the lasers. The lasers can be arranged in an array on a single chip. The lasers can be arranged in multiple single-chip arrays, and the arrays can be stacked on top of each other. The light source can further include a lens positioned between the laser diode and the reflector. The lens can be adapted for focusing the light from the laser diode in along the fast axis of the laser diode. The reflector can be in contact with the laser diode. A peak reflectivity of the reflector can be greater than a reflectivity of an output facet of the laser diode.

A combination of a high-power laser with a narrow bandwidth reflector results in a narrow spectral bandwidth and high beam quality radiation beam output from the combination. Moreover, the spectral output from the laser-reflector combination has a high short-term and long-term thermal stability.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention, suitable methods and materials are described below. All publications, patent applications, patents, and other references mentioned herein are incorporated by reference in their entirety. In case of conflict, the

present specification, including definitions, will control. In addition, the materials, methods, and examples are illustrative only and not intended to be limiting.

Other features and advantages of the invention will be apparent from the following detailed description, and from the claims.

DESCRIPTION OF DRAWINGS

FIG. 1 is a schematic perspective view of a laser diode.

FIG. 2 is a graph of a spontaneous emission spectrum for a laser diode.

FIG. 3 is a graph of a spontaneous emission spectrum and a laser spectrum for a laser diode.

FIG. 4 is a schematic top view of a laser system, the lateral beam profile, and the output emission spectrum from the system.

FIG. 5 is a schematic side view of a laser system, the vertical beam profile, and the output emission spectrum from the system.

FIG. 6a is a spectral reflectivity spectrum of a reflector.

FIG. 6b is a spatial reflectivity spectrum of a reflector.

FIG. 6c is a schematic diagram of a photo-thermo-refractive material.

FIG. 7 is a schematic side view of a laser system, the vertical beam profile, and the output emission spectrum from the system.

FIG. 8 is a schematic top view of a laser system, the lateral beam profile, and the output emission spectrum from the system.

FIG. 9 is a schematic top view of a laser system, the lateral beam profile, and the output emission spectrum from the system.

FIG. 10 is a schematic top view of a laser system, the lateral beam profile, and the output emission spectrum from the system.

FIG. 11 is a schematic perspective view of a laser array system.

FIG. 12 is a graph of an absorption spectrum of a fiber laser medium.

FIG. 13 is a graph of absorption spectra of laser media.

FIGS. 14a and 14b are graphs of an absorption spectrum of a laser medium and the emission spectrum of a diode laser.

FIG. 15 is a graph of the center wavelength of a laser diode as a function of the laser diodes position on a semiconductor wafer.

FIG. 16 is a graph of multiple laser diode emission spectra for different drive currents.

FIG. 17 is a graph of multiple laser diode emission spectra for different emitters in a laser diode array as a function of position.

FIG. 18 is a schematic diagram of a system for combining different laser beams.

Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

A high-power semiconductor diode lasers or diode laser array can be optically coupled to a narrow spectral and spatial bandwidth reflector to control the modes of the laser light generated in the laser, such that only desired modes are supported. The radiation reflected by the reflector back into the light source aids in discrimination undesired spatial and spectral modes, which stabilizes the laser light about the narrow spatial and spectral bandwidth. The apparatus and method can be used for many different material systems as well as all semiconductor diode laser sources for both discrete elements and laser arrays.

FIG. 1 shows, a semiconductor laser diode 10 that includes a body 12 of semiconductor material or materials having a bottom surface 14, top surface 16, end surfaces 18, and side surfaces 20. Material layers within the body 12 can be grown epitaxially, e.g., through metal organic chemical vapor deposition (MOCVD), liquid phase epitaxy (LPE), or molecular beam epitaxy (MBE). Body 12 includes a waveguide region 22 that extends across the length of the laser body 12. Within the waveguide region 22 is an active region 24 in which photons are generated when an appropriate electrical bias is placed across the diode 10. The active region 24 may be composed of any structure well known in the laser diode art that is capable of generating photons. For example, the active region 24 can include one or more $In_xGa_{1-x}As_yP_{1-y}$ quantum wells, where $0 \leq x \leq 1$ and $0 \leq y \leq 1$. On each side of the waveguide region 22 is a separate clad region 28 and 30. The waveguide region 22 also includes waveguide layers 26 on each side of the active region 24 that are composed of semiconductor material having an index of refraction that is greater than the cladding layer's 28 and 30 index of refraction.

Also, the clad regions 28 and 30 are at least partially doped, such that they have opposite conductivity types. For example, the clad region 28 between the waveguide region 22 and the top surface 16 of the body 12 may be of p-type conductivity and the clad region

30 between the waveguide region 22 and the bottom surface 14 of the body 12 may be of n-type conductivity.

The various regions of the body 12 may be made of any of the well-known semiconductor materials used for making laser diode, such as, but not limited to, gallium arsenide, indium phosphide, aluminum gallium arsenide, indium gallium arsenide, indium gallium phosphide, and indium gallium arsenide phosphide. The individual compositions and thicknesses of the active region 24, the waveguide layers 22, and the clad regions 28 and 30 can be chosen such that the overlap of the vertical laser cavity mode over the waveguide region 22 is large (e.g., more than about 90%), as described in U.S. Patent 5,818,860, which is incorporated herein by reference in its entirety. For example, the vertical thickness of the active region can be on the order of the a few nm, while the vertical thickness of the waveguide region 22 is on the order of the wavelength of the radiation emitted from the laser 10.

The body 12 can be fabricated such that the upper clad region 28 includes a ridge 32 that is in ohmic contact with a contact layer 34 of a conductive material, such as a metal. The contact layer 34 is in the form of a stripe that extends between the end surfaces 18 of the body 12 and is narrower than the width of the body 12, i.e., the distance between the side surfaces 20 of the body 12. For example, the width of the contact stripe can be equal to the width of the stripe. Alternatively, the body can be fabricated without a ridge 32, and a contact stripe 34 can be deposited on a flat top surface 16 of the body 12. A contact layer 36 of a conductive material, such as a metal, is on and in ohmic contact with the n-type conductivity clad region 30. The contact layer 36 extends across the entire area of the bottom surface 14 of the body 12.

When an electrical bias is applied between the top contact layer 34 and the bottom contact layer 36, a current flows vertically through the body 12 of the laser diode 10. The width of the contact stripe 34 is a factor in determining the spatial profile of charge carriers (electrons and holes) that pass through the active region 24 of the laser 10. Holes that enter the active layer 24 from the upper contact layer 34 recombine with electrons that enter the layer 24 from the bottom contact layer to generate photons spontaneously. The spectrum of spontaneously generated light depends on the materials of the active region 24, and on other factors, such as, for example, the temperature of the body 12 and strain on the materials in the active region 24 due to lattice mismatch with materials in the surrounding regions 26, 28,

and 30. A hypothetical intensity (I) vs. wavelength (λ) spectrum 202 for spontaneously generated light in a laser diode 10 at a fixed temperature is shown in FIG 2. However, the spectrum shown in FIG 2 is temperature dependent, and spectra for the same laser diode 10 operating at a higher temperature 204 and a lower temperature 206 are also shown in FIG 2.

A change in diode laser 10 temperature can occur due to a change in ambient temperature, change in the thermal resistance of the heat sink, change in the heat generated within the laser diode due to increased current or reduced efficiency and by other means.

End surfaces 18a and 18b of laser diode 10 can be totally or partially reflecting, such that when electromagnetic radiation generated in active region 24 reaches an end surface 18a or 18b it is reflected back into the active region, where it can cause the stimulated emission of additional radiation having the same, or nearly the same, wavelength and phase as the reflected radiation. For example, one end surface (e.g., a rear surface) 18a can have a reflectivity of about 95% and the other end surface (e.g., a front surface) 18b can have a reflectivity of about 1% - 20%. The radiation is emitted into an optical mode of mode order N of a cavity that is defined by the geometry of body 12. When the rate of stimulated emission of radiation in the optical mode exceeds the radiation loss rate in the material, a threshold is exceeded above which gain occurs, and laser action begins in the optical mode of the body 12.

As shown in FIG 3, when the device 10 operates above threshold, the output radiation spectrum 302 resembles the spontaneous emission spectrum 202 for the device, with a sharp peak 304 around a wavelength, λ_o, for which stimulated emission most strongly exceeds the loss. The peak wavelength, λ_o, is approximately equal to the wavelength at which the spectrum 202 reaches a maximum, and the full-width at half maximum (FWHM) spectral width $\Delta\lambda$ of the peak 304 is a few nm for a peak wavelength of about one micron. Loss in the body 12 causes an increase in the temperature of the laser diode, which can shift the spontaneous emission spectrum of the laser diode 10, which results in a shift in the center frequency of the output spectrum. Thermal aging of a laser diode 10 can also cause the peak wavelength, λ_o, at a fixed ambient temperature, to shift over the lifetime of the device. Stress induced in the laser diode by mounting, or thermally induced stress through different coefficients of expansion of the heat sink, the solder, and the laser diode material can also change the spontaneous emission spectrum as well as the laser emission wavelength.

A wider contact stripe 34 generally increases the effective width of the active region 24 in which electron-hole recombination occurs, resulting in the generation of a greater number of photons per time and a higher output power from the laser 10. The effective width of the active region can also be controlled in other laser structures. For example, the effective width of the active region 24 can be determined by the width of the ridge 32 to selectively change a lateral index step for optical mode confinement, by the width of a buried heterostructure configuration, or by the width of an opening between ion-implanted reduced conductivity regions in the active region 24.

However, a wider contact stripe 34 also increases the number of lateral modes N in which laser action can occur, which results in a beam profile of the laser diode 10 that includes contributions from all of the above-threshold modes. A high order mode output beam of the laser diode 10 has a beam quality that is lower than that of a low order mode beam (e.g., a Gaussian beam, having N = 1), because the lowest order (i.e., N = 1) mode has the highest beam quality (i.e., Q = 1). Moreover, higher order modes are generally degenerate and therefore multiple degenerate higher order modes can compete in the beam profile, resulting in peaks and troughs in the spatial intensity spectrum of both the emitted laser light and the light that oscillates within the laser cavity.

When parameterizing a laser's performance in terms of the laser's output power, the spectral line width of the output light, and the spatial beam quality of the output light, it can be helpful to combine these performance characteristics into single parameter, namely the brilliance, B*, of the laser. The brilliance of a light source is defined as the number of photons emitted into a solid angle, $\partial\Theta$ per time t, divided by the source area δA and wavelength interval $\partial\lambda/\lambda$. Thus,

$$B^{*} = \frac{N}{t \cdot \partial\Theta^{2} \cdot \partial A \cdot \left(\partial\lambda/\lambda\right)}. \qquad (1)$$

For a laser beam with a center wavelength λ, a beam waist radius ω_o, and a far-field half divergence angle of θ_o,

$$B^{*} = \frac{P \cdot \lambda}{hc\pi^{2}\theta_0^{2} \cdot \omega_0^{2} \cdot \left(\partial\lambda/\lambda\right)}, \qquad (2)$$

where *h is* Plank's constant and c is the speed of light. Using the dimensionless definition of the beam quality Q,

$$Q = \frac{\lambda}{\pi \omega_o \theta_o}, \tag{3}$$

the brilliance can be written as

$$B^* = \frac{P \cdot Q^2}{h \cdot c \cdot \Delta\lambda} \propto \frac{P \cdot Q^2}{\Delta\lambda}, \tag{4}$$

where P is the output power of the light source.

The brilliance of a light source (e.g., a laser) is considered a conserved quantity of the beam and cannot be increased by resonator-external, passive optical elements. Therefore, to improve the brilliance of a source it is important to improve the beam quality, Q, and reduce the spectral width $\Delta\lambda$ of the output light.

Because the maximum beam quality ($Q = 1$) is achieved by a Gaussian beam profile, a Gaussian beam provides the maximum possible brilliance for a laser beam of given power and spectral width. A laser diode 10 generally emits a beam having a nearly Gaussian profile in the vertical direction, also known as the fast axis of the laser (i.e., between the top surface 16 and the bottom surface 14). A laser diode 10 having a narrow stripe 34 width on the order of the wavelength of the output light also emits a beam having a nearly Gaussian profile in the lateral direction, also known as the slow axis of the laser (i.e., between the side surfaces 20 of the laser 10).

However, to achieve high power output from a semiconductor laser diode 10, a relatively wide effective lateral width of the active region 24 is used to generate laser light. This can be accomplished, for example, by injecting current into the active region 24 through a relatively wide contact stripe 34. The output power from laser 10 depends approximately linearly on the width of the contract stripe 34. A relatively wide effective active region 24 generally improves the efficiency and reliability of the semiconductor laser diode 10. The reliability and efficiency can be affected by the operating temperature of the active region 24, and the operating temperature depends on the thermal resistance of the laser 10. The thermal resistance of the laser 10 is inversely proportional to the length multiplied by the effective width of the active region 24. Therefore wide effective area lasers 10 can allow higher output powers at reasonable reliability (junction temperature) than narrow devices.

Such lasers 10 may be known as "wide stripe emitters," broad stripe emitters," or "multimode devices." However, when the effective lateral width of the active material 24 is greater than several times the laser output wavelength, λ_o, gain can occur in higher order

spatial modes of the resonant cavity, and the spatial beam quality, Q, of the output laser light can be reduced.

The beam emitted by wide stripe emitter 10 is astigmatic and has different beam qualities for the lateral (slow axis) and vertical (fast axis) directions. The overall beam quality can be defined as the product of the square root of the qualities for the two axes:

$$Q = \sqrt{Q_{Fast}} \cdot \sqrt{Q_{Slow}} = \frac{\lambda}{\pi \cdot \omega_0 \cdot \theta_0 \cdot \sqrt{N_{Fast} N_{Slow}}}, \qquad (5)$$

where Q_{Fast} and Q_{Slow} refer to the beam quality in fast and slow axis, respectively, while N_{Fast} and N_{Slow} refer to the number of spatial modes in the fast and slow axis, respectively. The number of modes in the fast axis for laser 10 is typically equal to unity. Therefore, the output beam in this direction is nearly Gaussian, and the beam quality in this direction nearly 1.

In the slow axis, the number of modes increases with increasing width, d, of the contract stripe 34. For wide contact stripes 34 when many lateral modes exist, the number of modes can increase approximately linearly with width d. Thus, the slow axis beam quality can be written as

$$Q_{Slow} = \frac{\lambda}{\pi \cdot \omega_0 \cdot \theta_0 \cdot \sqrt{N_{Slow}}} \cong \frac{\lambda}{\pi \cdot \omega_0 \cdot \theta_0 \cdot \sqrt{d}} \qquad (6)$$

Because the slow axis beam quality depends inversely on the square root of the width of the contract stripe 34 and the output power of the laser 10 depends approximately linearly on the width of the contact stripe 34, increasing the power by increasing the stripe width d does not necessarily increase the brilliance, B^*, as is evident from equation (4). To increase the brilliance of the laser 10, the slow axis beam quality must be maintained or improved as the power of the laser 10 is increased.

As shown in FIG. 4 and FIG. 5, coupling the output beam 402 of a multimode laser diode 10 mounted on a heat sink 420 to an external, narrow bandwidth reflector 404 can provide optical feedback 406 to the laser diode 10. Comparison of the horizontal divergence, θ_H, and the vertical divergence, θ_V, of the output beam 402, as illustrated in FIGS. 4 and 5, respectively, shows that the divergence is greater about the fast axis of the laser (i.e., in the vertical direction) than about the slow axis of the laser (i.e., in the horizontal direction). This is because the vertical thickness of the active layer 24 is much smaller than the layer's effective lateral width, which is determined, in part, by the width of the contact stripe 34.

However, because the vertical thickness of the active region in the laser 10 is on the order of the output wavelength, only the lowest-order vertical cavity mode experiences gain in the laser 10, and the output beam 96 is diffraction limited in the vertical direction.

A narrow spectral bandwidth portion of the laser emission spectrum is partially reflected by reflector 404 back into the resonant cavity of the laser 10 where it self-seeds the laser, thus providing enhanced feedback to the laser over the narrow bandwidth of the reflector 404. The spectral reflectivity bandwidth of the reflector can be characterized by a peak reflectivity of about 5% to about 95% that is centered around the peak wavelength, λ_p, of the laser diode 10 and a FWHM reflectivity of about 0.05 nm to about 1.0 nm. For example, as shown in FIG. 6a, the spectral reflectivity spectrum 120 of the reflector 404 can have a profile that is has a peak of about 85% at a 940 nm and quickly decreases to higher and lower wavelengths, for instance to 50% of the peak value at 935 nm and 945 nm.. The reflectivity of the reflector 404 is similarly narrowly peaked about a particular input angle, ϕ_o, of laser light with respect to an axis in the reflector (e.g., an axis that is normal to a front surface 408 of the reflector 404). The reflectivity of the reflector can have a peak reflectivity of about 5% to about 95% at ϕ_o, which rapidly decreases at higher and lower angles, for example to 50% of the peak value at +/- 0.01° centered around ϕ_o. For example, as shown in FIG. 6b, the angular reflectivity spectrum 122 of the reflector 404 can be peaked about an angle of zero degrees to the normal of the front surface 408 of the reflector 404 and can have a FWHM width of about 0.02 degrees.

High order modes in the lateral direction, with larger far field divergence at the given beam waist (i.e., given by the lateral width of the stripe 34) experience less feedback than low order modes. Therefore, the higher order modes are discriminated, and laser action does not occur in the higher order modes, only in the lower order modes.

These effects increase the brilliance of the output beam by increasing the beam quality Q and decreasing the spectral width $\Delta\lambda$, without reducing the output power P.

Narrow bandwidth reflector 404 can be, for example, a three-dimensional transparent material that includes a pattern of index of refraction changes. Such patterned materials can be, for example, volume diffractive gratings, volume Bragg gratings (VBG), or holographic gratings. Referring to FIG. 6c, a volume diffraction grating 600 can be created by exposing a photo-thermo-refractive (PTR) material 602 to a periodic light intensity pattern to write the

pattern into the material 602. The periodic light intensity pattern can be recorded in the material 602, for example, by interfering two monochromatic, coherent light beams 604 in the material.

The creation of volume diffraction gratings and the photo-sensitive materials used for the gratings have been described in "High-Power Incoherent Beam Combining with Bragg Grating in Photosensitive Glasses," by Igor V. Ciapurin, Leonid B. Glebov and Martin Stickley, Proceedings of Solid State and Diode Lasers Technical Review. Albuquerque (2002), HPFIB4, and "Volume diffractive elements in photosensitive inorganic glass for beam combining," by L.B. Glebov, SSDLTR'2001 Conference Digest, Paper Code FA-5, Albuquerque, NM, May 21-24, 2001, which are incorporated herein by reference in their entirety.

The PTR material 602 can be, for example, a sodium-zinc-aluminum silicate doped with cerium, silver, and fluorine. A grating can be recorded in the material 602 by first exposing the material to an interference pattern of two or more ultraviolet lasers (e.g., 35 mW He-Cd lasers having a wavelength of 325 nm), which creates an interference pattern in the intensity of the ultraviolet (UV) radiation within the material. After exposure to the UV radiation, the material 602 is developed thermally to induce a crystal phase precipitation of the exposed UV pattern in the material. A refractive index contrast of up to about 0.001 between high-index portions 610 and low-index portions 612 of material 602 can be achieved in this manner.

The angle, Ψ, between the two beams 604 determines the spacing between the high-index portions 610 and low-index portions 612 of material 602. Volume diffractive gratings can be created that have a thickness 614 of up to 5 mm and a cross section that is much greater than the cross section of the output beam from the laser 10. For example, the cross section of the volume diffractive grating can be 10 mm by 10 mm. The spacing of the high-index portions 610 and the low-index low index portions 612 determines the wavelength of peak reflectivity for the reflector 404, and thickness of the material 614 and the repeatability of the high-index to low-index spacing over the thickness of the material determines the FWHM of the reflectivity spectrum 120. The peak reflectivity value of the reflector is determined by the refractive index contrast in the volume diffraction grating 600 and the thickness 614 of the grating.

Referring again to FIG. 4, the reflector 404 can be [?] placed in front of the front end surface 18b of laser 10, such that light emitted from the laser 10 can be reflected by the reflector 404 back into the active region 24 of laser 10. When a volume diffraction grating is used as the reflector 404, light emitted from the laser 10 enters the grating at an angle that is, on average, perpendicular to the faces high-index 610 and low-index portions 612 of the grating pattern. Alternatively, light emitted from the laser 10 can enter the grating in a direction that is parallel to the grating pattern. The alignment tolerance of the reflector 404 depends, in part, on the reflectivity of the front end surface 18b and on the reflectivity at normal incidence of the reflector 404. In particular, the effective reflectivity of the reflector 404 (the fraction of the incident power that is coupled back into the semiconductor active area 24) must be greater than the reflectivity of the front end surface 18b to discriminate spatial and spectral modes. The stronger the effective feedback from the volume diffraction grating, the less sensitive the alignment tolerances will be.

Because the feedback 406 into the laser 10 is highly selective in the angular and the spectral emission spectra, the reflector 404 effectively discriminates higher order spatial as well as spectral modes from the laser beam 94 that is ultimately emitted from the laser diode 10 and reflector 404 system. For example, modes with significant on-axis intensity are reflected most strongly by the reflector 404 and experience feedback and gain in the laser-reflector system, whereas high-order modes are reflected relatively less by the peak reflectivity of the reflector 404, and therefore experience less feedback and more loss than gain in the system.

Thus, the number of spatial modes N in the slow axis intensity profile 94 of the output beam is substantially reduced when the reflector 404 is present. This reduces the divergence angle 93 of the output beam, as compared with the divergence of the output beam of the laser 10 operated without the narrow band reflector 10, because the beam waist remains constant and effectively increases the beam quality and brightness of the output beam 94.

As explained above, because only the lowest-order vertical cavity mode resonates in the laser cavity and the output beam is close to being diffraction limited in the fast axis, spatial modes are not discriminated in the fast axis direction, and the fast axis divergence is relatively unaffected by the presence of the narrow band reflector 404. However, as shown in FIG. 7, the output beam 98 can be focused in the fast axis direction by a cylindrical lens

430 located between the laser 10 and the narrow bandwidth reflector 404, so that the beam is collimated 97 in the fast axis, which increases the amount of feedback from the reflector 404 and therefore improves the mode discrimination.

As shown in FIG. 8, a slow axis lens 101 can be placed between laser 10 and reflector 404 to change the divergence angle of the different spatial modes in the slow axis, which can achieve additional reduction in feedback from reflector 404 for these higher order modes. Slow axis lens 101 can be a converging lens to collimate the beam or can be a diverging lens to enhance mode discrimination by the reflector 404. The slow axis lens 101 can be used alone or in combination with the fast axis lens 430. The optical effect of the two lenses 101 and 430 can also be combined into a single optical element that focuses (or defocuses) the output beam along both the fast and slow axes.

Similar to the reduction of spatial modes and reduction of divergence in the output beam profile, the narrow spectral bandwidth of the reflector 404 enhances feedback into the laser 10 for wavelengths that correspond to the spectral reflectivity spectrum of the reflector 404, thus discriminating spectral modes that lie outside the reflectivity spectrum of the reflector 404. This line width of the radiation spectrum 95 emitted from the laser diode 10 and reflector 404 system is narrower than the spectrum 15 of radiation emitted from the laser diode 10 in the absence of the reflector 404. For example, the FWHM line width of the spectrum 95 can be less than on nanometer compared to the several nanometer wide spectrum 15.

Because the reflectivity spectrum of the reflector 404 is relatively narrow and the intrinsic absorption of the VBG is small, relatively little radiation, and therefore heat, is absorbed in the reflector. In addition, PTR glass of the reflector 404 does not experience Joule heating as the laser diode 10 does when driven by an electrical current, so optical properties of the reflector 404 are relatively thermally stable in comparison to the optical properties of the laser 10. Because of this, the reflectivity spectrum of the reflector 404 is relatively thermally stable compared to the spontaneous emission spectrum of the laser 10. Thus, the peak output wavelength, λ_o, of the laser-reflector system is not determined only by the thermally-sensitive peak of the spontaneous emission spectrum 302 of laser 10, but also by the thermally-stable, wavelength-dependent feedback from reflector 404. As a result, the peak wavelength of the laser diode 10 and reflector 404 system is relatively insensitive to the temperature of the system. For example, in the absence of reflector 404, the output

wavelength of the laser diode 10 can shift from about 807 nm to about 812 nm as the temperature of the laser diode's environment rises from about 20 °C to about 55 °C. When the reflector 404 provides feedback into the laser 10, the output wavelength of the laser diode 10 shifts by less than about 0.2 °C over this temperature range. The output wavelength of the laser diode 10 is similarly stabilized by the reflector 404 against age-induced drifts in the output wavelength. As another example, the presence of the reflector 404 can reduce the dependence of the peak wavelength on the drive current by a factor of about 2.5.

As shown in FIG. 9, reflector 404 can be brought into direct contact with the laser diode 10. Direct contact between and end surface 18b of the laser 10 and the front surface 408 of the reflector 404 will improve the spatial and spectral beam quality of the output laser radiation, without using a fast axis collimation lens 430. In addition, when the laser 10 and reflector 404 are in direct ("optical") contact, heat removal from the laser facet is improved by providing an additional direction of solid-state conductive heat transport from the laser diode 10. Reduction of thermal stress to the end surfaces ("facet") 18a and 18b of the laser 10 may improve the catastrophic optical mirror damage (COMD) level of the laser diode 10. Good thermal contact can be achieved between an end surface 18 of the laser 10 and a VBG reflector 404 because both have optically flat surfaces that make good optical contact with each other.

As shown in FIG. 10, front surface 408 of the reflector 404 can be attached or placed close to the end surface 18a of the laser 10, such that the reflector acts as the rear mirror of the laser 10. In this case the facet reflectivity of the end surface 18a of laser 10 can be chosen to be at least semi-transparent, if not totally transparent, while the reflector 404 having a reflectivity peak at the desired angle and wavelength of about 95% or more will ensure maximum reflection and feedback 406 of the beam. The angular and spectral selectivity will again proficiently ensure the discrimination of high order spatial modes and decrease the spectral line width from its original shape 15 to the narrow shape 95.

FIG. 11 shows an array 500 of broad stripe emitters 10 having a slow axis intensity profile 502 and a fast axis intensity profile 504 in optical communication with a narrow bandwidth reflector 506 that extends along the lateral width of the entire array. As with the single laser diode 10 and reflector 404 system described above, the array 500 and narrow bandwidth reflector 506 cause selective feedback to the individual emitters 10 of the array 500, which results in improved thermal stability of the peak wavelength of the array, a

narrower vertical divergence angle of light from the array, and improved beam quality of light form the array.

Several arrays 500 of broad stripe emitters 10 can be stacked on top of each other to create a high power diode laser stack. Typically, 12 arrays 500 are stacked on top of each other with a vertical height of the stack being about 2 mm. Such a stack can capable of emitting 600 Watts of continuous output laser power. The individual arrays 500 of the stack can be fast axis collimated, just like the individual arrays.

As with the single laser diode 10 and reflector 404 system described above, the stack of arrays 500 can be combined with a narrow bandwidth reflector that extends over the entire height of the stack. This will cause selective feedback to the entire stack of arrays 500, resulting in improved thermal stability of the peak wavelength of the stack of arrays 500, a narrower vertical divergence angle of light from the stack of arrays, and improved beam quality of light form the stack of arrays 500.

The laser diode 10 and narrow spectral and spatial bandwidth reflector 404 system achieve a simultaneous improvement the beam quality and the reduction of the spectral width of the emitted radiation while maintaining the output power of the laser 10 nearly constant, and therefore increase the brilliance of the laser diode 10.

The combination of the laser diode 10 and the narrow bandwidth reflector 404 can be used to provide pump light to a solid state laser. For example, FIG. 12 shows an absorption spectrum 41a and an emission spectrum 41b of a Yb:Glass fiber laser, and FIG. 13 shows an absorption spectrum 42 of a Nd:YAG rod laser and an absorption spectrum 43 of a Yb:YAG disc laser. These three solid-state laser media are often used for high-power (e.g., multi-kW) laser applications. The laser media can be pumped with high-power diode lasers, however, the input pump power from the diode laser absorbed in the laser medium must exceed the output power from the solid state laser medium. Thus, to achieve multi-kW laser output from the solid state laser medium, the power of the pump diode laser must also be in the multi-kW range.

Referring to FIG. 14a, absorption of pump diode laser power depends on the overlap of the solid-state laser medium absorption line 40 and the emission line 50 of the pump diode laser. Absorption of pump diode laser power also depends on the absorption length of the pump radiation in the solid state laser medium. The integral of the overlap function 60 of the laser medium absorption line 40 and the pump laser emission line 50 is generally increased

when the peak emission wavelength of the diode laser is approximately equal to the center wavelength of the absorption spectrum 50. The overlap integral also generally increases when the line width and spectrum of the emission spectrum 40 is smaller or at most of equal (FWHM) to that of the absorption spectrum 50.

As shown in FIG 14b, when the peak wavelength of the pump laser emission spectrum 50' differs from the center wavelength of the absorption spectrum 40 by a few nm, the integral of the overlap function 60' between the two spectra is rather poor, even though the line width of the emission spectrum 40 is smaller than that of the absorption spectrum 50. Many different effects can lead to a mismatch between the center wavelength of the laser diode and the center wavelength of the emission spectrum 40 and therefore reduce the optical-optical efficiency of a diode pumped solid-state lasers.

For example, as shown in FIG 15, when many laser diodes are created from a single semiconductor wafer, the center wavelength of a laser diode can depend on the position on the semiconductor wafer from which the laser diode is created because epitaxial growth does not occur entirely homogenously across the wafer. Generally, the wavelength of laser diodes produced near the center of a wafer is highest and diminishes for positions at greater radial distance from the center of the wafer. The wafer-position dependence of the peak wavelength of laser diodes produced from a three inch wafer can be about 20 nm, which, for laser diodes having emission spectrum line widths of a few nm, would render many lasers from the wafer useless for pumping a laser medium absorption line that is a few nm wide.

As another example, as shown in FIG 16, the center wavelength and line width of the pump diode laser emission spectrum depends on the driving current and therefore on the output power from the laser. Characteristic emission spectra 52a, 52b, 52c, 52d, 52e, and 52f of a laser diode operated at 0.8 A, 1.5 A, 2.0 A, 2.5 A, 3.0 A, and 3.5 A, respectively, show that the peak wavelength of the laser diode can shift by more than 6 nm as the drive current is increased from 0.8 A to 3.5 A.

As a further example, as shown in FIG 17, the center wavelength of an individual emitter of an array can depend on the position of the emitter in the array (e.g., due to a stress-induced wavelength shift associated with the mounting of the array on a heat sink). Characteristic emission spectra 53a, 53b, 53c, 53d, 53e, and 53f of individual emitters located at different positions in the array show that the wavelength spectrum 53a of an emitter at the center of the array has a peak wavelength that is shorter that the peak

wavelength of the spectrum 53f of an emitter located at an edge of the array. There is an additional difference in center wavelength between the emission spectrum at the left most emitter.53e and the right most emitter 53f. Thus, the combination of emission spectra from all individual emitters effectively causes line broadening of the emission spectrum (53) of the entire array.

All these effects affect the coupling efficiency between the input pump light and the output laser light in a diode pumped solid-state laser. However, stabilization of the pump diode laser wavelength by the narrow bandwidth reflector 404 reduces the deleterious aspects of these effects, by locking the emission wavelength of the high-power broad area strip array of broad area or single mode stripes and stack of arrays to a specific central wavelength defined by the reflectance band of the reflector 404 and additionally narrowing the spectral line width of the pump radiation emission spectrum.

In addition to the improvement in spectral behavior, the improved beam quality of light from the laser diode – narrow bandwidth reflector system is favorable for solid state laser pumping because it allows a narrower focusing of the beam and therefore smaller solid state laser media or much reduced alignment requirements between the pump beam and the laser medium.

As shown in FIG. 18, several narrow bandwidth reflectors 73 and 74 can be used combine multiple laser beams 54a, 54b, and 54c having different wavelengths, λ_1, λ_2, and λ_3, respectively into a single beam 54. The reflectivity spectrum of the narrow bandwidth reflector 73 is selected to reflect beam 54b having wavelength λ_2 but to be transparent to beam 54a having wavelength λ_1. Similarly, the reflectivity spectrum of the narrow bandwidth reflector 74 is selected to reflect beam 54c having wavelength λ_3 but to be transparent to beams 54a and 54b having wavelengths λ_1 and λ_2, respectively. Because the reflectivity spectra of the reflectors 73 and 74 are relatively narrow, the individual beams 54a, 54b, and 54c can be combined without sacrificing power or beam quality of the combined output beam 54.

OTHER EMBODIMENTS

It is to be understood that while the invention has been described in conjunction with the detailed description thereof, the foregoing description is intended to illustrate and not limit the scope of the invention.

WHAT IS CLAIMED IS:

1. A light source comprising:

a semiconductor laser diode; and

a narrow spectral and spatial bandwidth reflector in optical communication with the semiconductor diode laser and aligned with an output beam of the diode laser, such that a portion of the light in the output beam is reflected back into the laser by the reflector.

2. The light source of claim 1, wherein the reflector is a volume diffractive grating.

3. The light source of claim 1, further comprising multiple laser diodes aligned with respect to the reflector such that a portion of the light from each of the laser diodes is reflected back into the lasers.

4. The light source of claim 3, wherein the lasers are arranged in an array on a single chip.

5. The light source of claim 3, wherein the lasers are arranged in multiple single-chip arrays, and wherein the arrays are stacked on top of each other.

6. The light source of claim 1, further including a lens positioned between the laser diode and the reflector.

7. The light source of claim 6, wherein the lens is adapted for focusing the light from the laser diode along a fast axis of the laser diode.

8. The light source of claim 1, wherein the laser diode is a multimode laser diode when operated without the reflector.

9. The light source of claim 1, wherein the reflector is in contact with an output facet of the laser diode.

10. The light source of claim 1, wherein a peak reflectivity of the reflector is greater than a reflectivity of an output facet of the laser diode.

11. The light source of claim 10, wherein the reflectivity of the reflector and the reflectivity of the output and rear facets of the laser diode are selected to optimize the output power of the light source.

12. The light source of claim 10, wherein the reflectivity of the output facet is less than about 50%.

13. The light source of claim 10, wherein the reflectivity of the output facet is less than about 10%.

14. The light source of claim 10, wherein the reflectivity of the output facet is less than about 3%.

15. The light source of claim 1, wherein the reflector is in contract with a rear facet of the laser diode.

16. A light source comprising:

a semiconductor laser diode;

a narrow spectral and spatial bandwidth reflector in optical communication with the semiconductor diode laser and aligned with an output beam of the diode laser, such that a first portion of the light in the output beam is reflected back into the laser by the reflector, and a second portion of the beam is coupled out of the laser diode as a pump beam; and

a laser active medium that is absorbs at least a portion of the pump beam.

17. The light source of claim 16, wherein the laser active medium is an active medium of a rod laser.

18. The light source of claim 16, wherein the laser active medium is an active medium of a disk laser.

19. The light source of claim 16, wherein the laser active medium is an active medium of a fiber laser.

20. A light source comprising:

a first semiconductor laser diode;

a first reflector having a first narrow spectral and spatial bandwidth, the first reflector being in optical communication with the first semiconductor diode laser and aligned with an output beam of the first laser, such that a first portion of the light in the output beam is reflected back into the first laser by the reflector and a second portion of the beam is coupled out of the first laser;

a second semiconductor laser diode;

a second reflector having a second narrow spectral and spatial bandwidth, the second reflector being in optical communication with the second semiconductor diode laser and aligned with an output beam of the second laser, such that a portion of the light in the output beam is reflected back into the second laser by the reflector and a second portion of the beam is coupled out of the second laser;

a beam combiner for combining the second portion beam of the of the first laser and the second portion of the second laser.

21. A method of improving the beam quality and narrowing the spectral linewidth of a laser diode, the method comprising:

aligning a narrow spectral and spatial bandwidth reflector with an output beam path of the laser.

ABSTRACT

A light source includes a semiconductor laser diode and a narrow spectral and spatial bandwidth reflector in optical communication with respect to the semiconductor diode laser and aligned with the output beam of the diode laser, such that a portion of the light in the output beam is reflected back into the laser.

40220639.doc

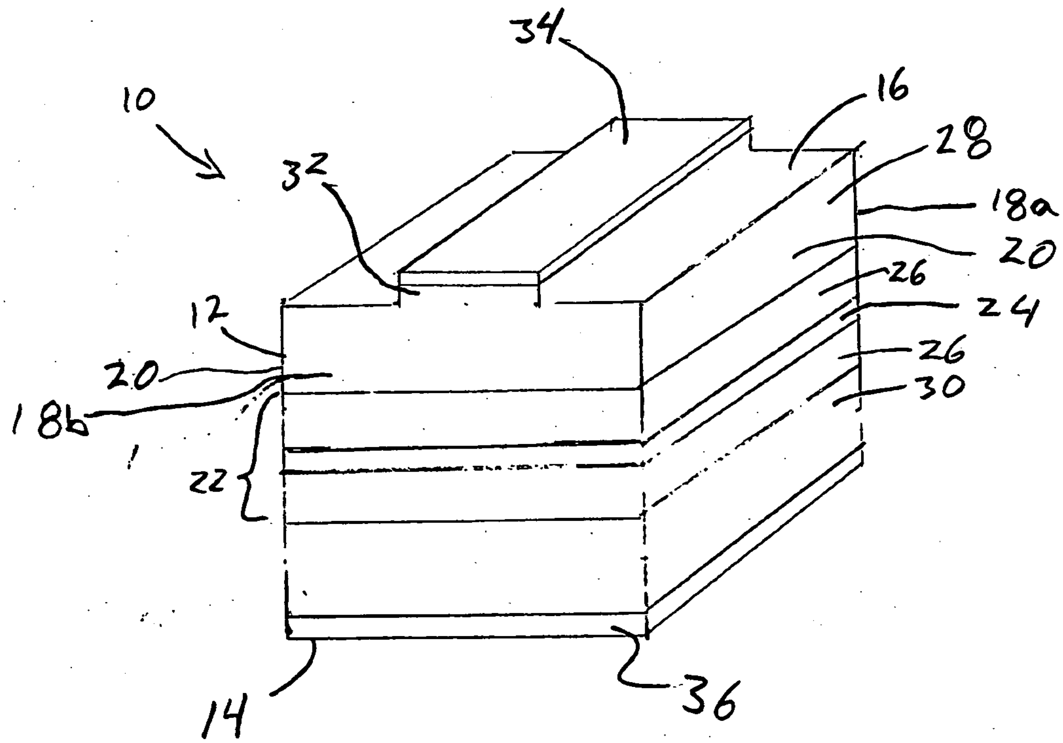


FIG. 1

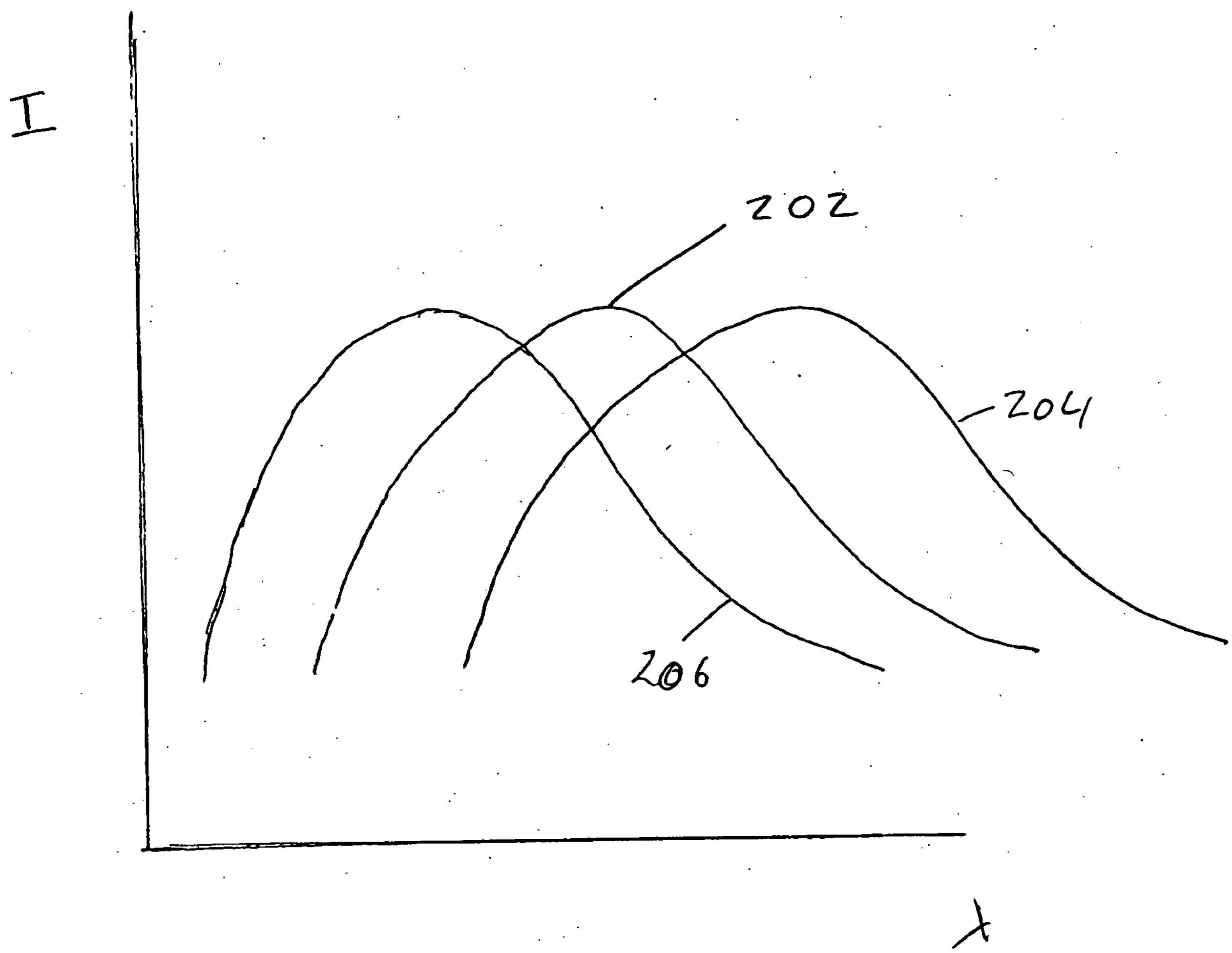


FIG 2

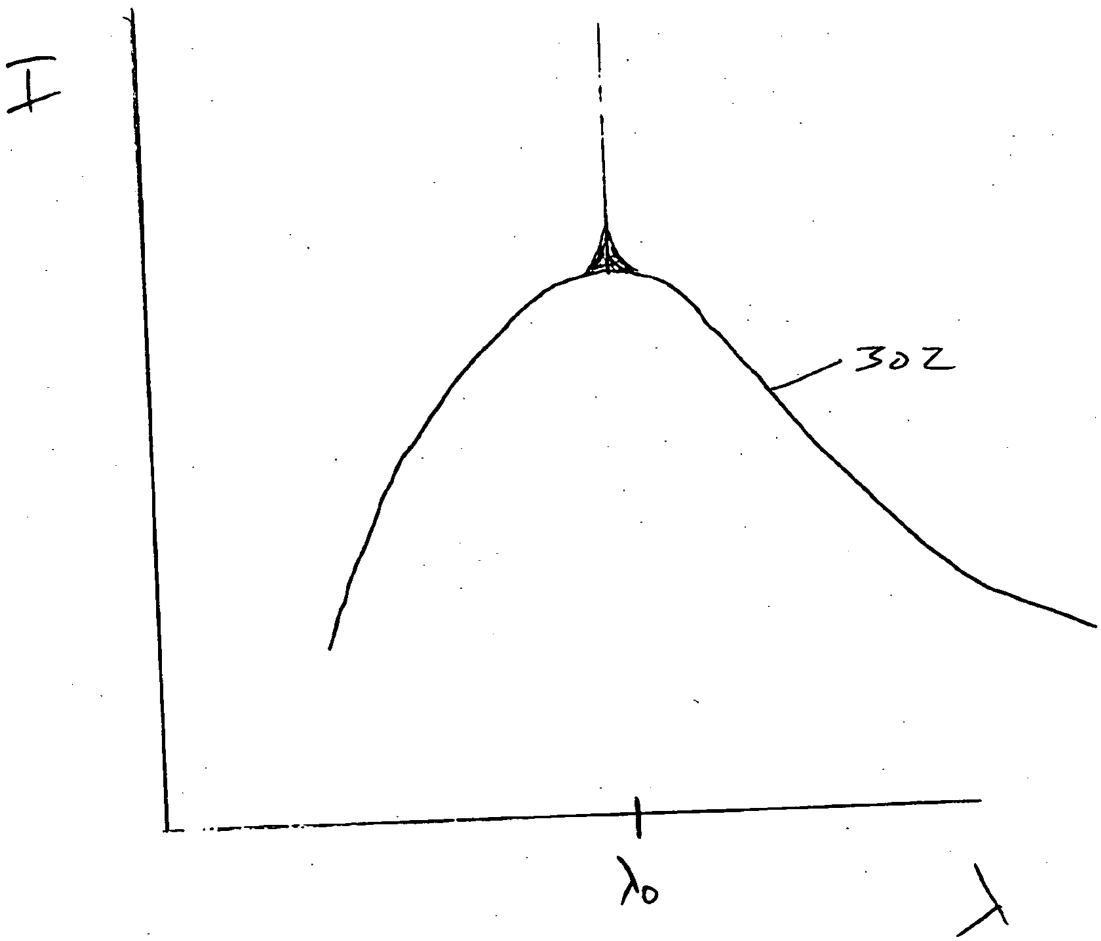


FIG 3

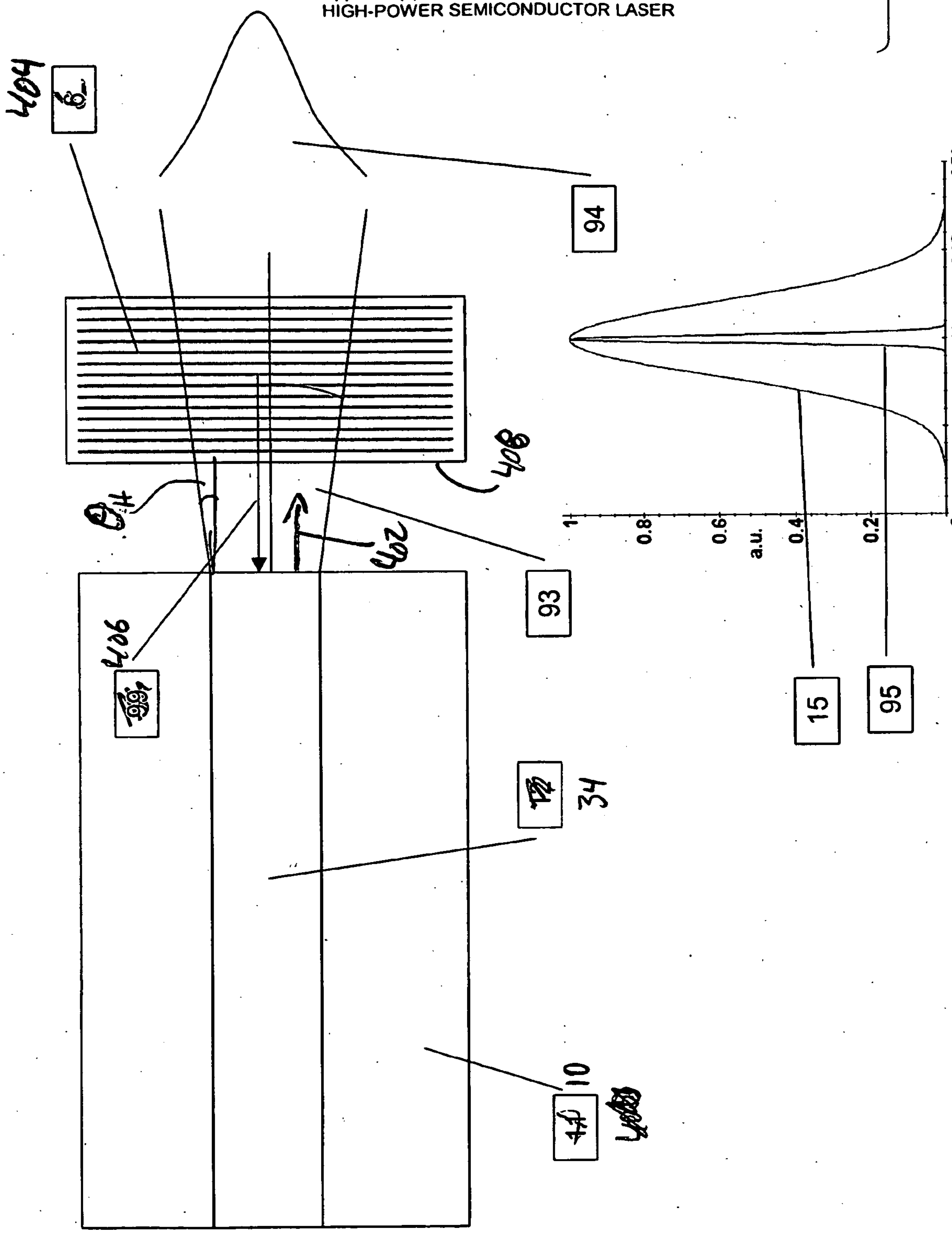

404
94
93
402
408
406
34
10
15
95
930
935
940
945
950
0
0.2
0.4
0.6
0.8
1
a.u.

Fig. 4

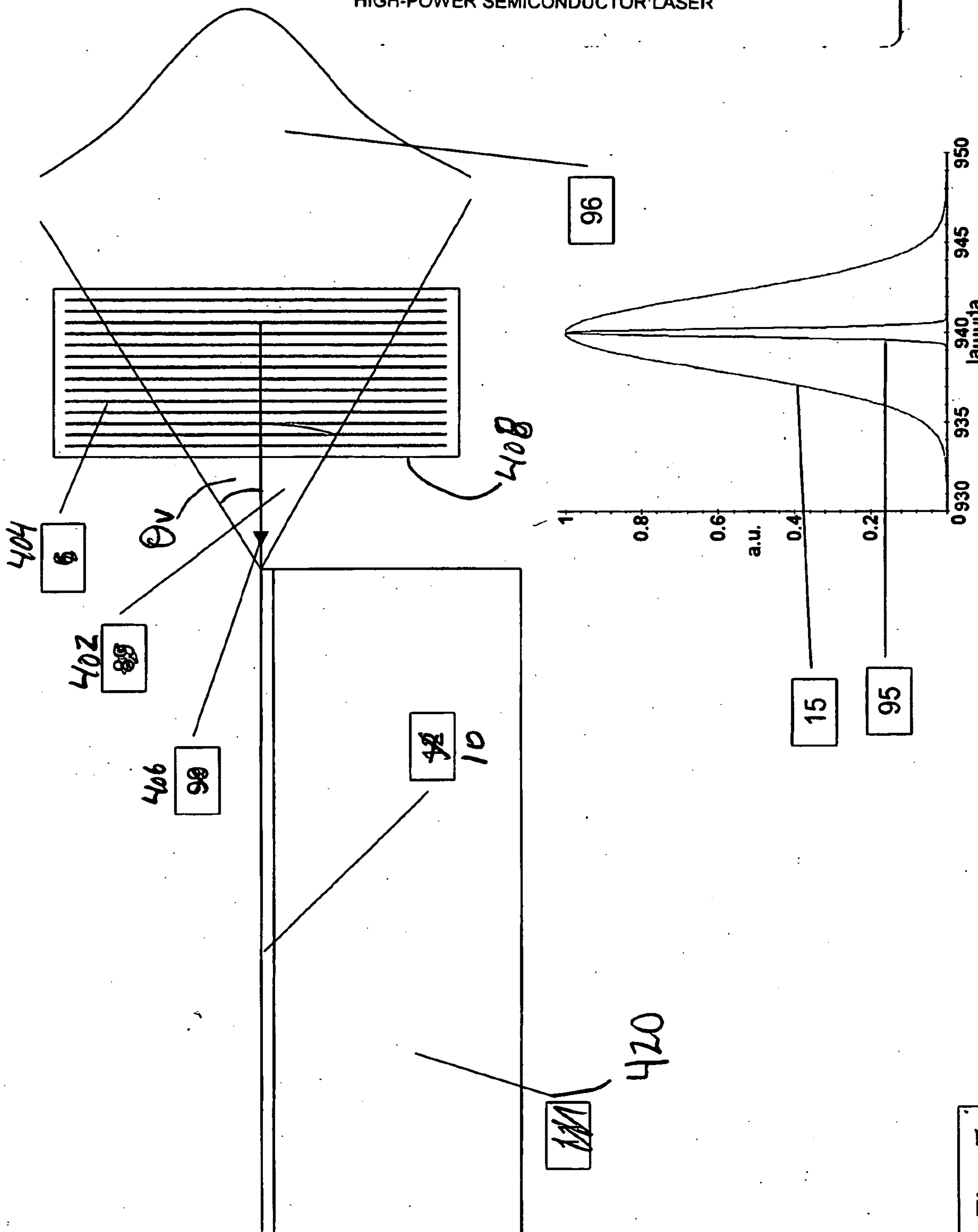

96
404
402
406
10
420
408
θ_v
15
95
a.u.
lamda
0.2
0.4
0.6
0.8
1
930
935
940
945
950

Fig. 5

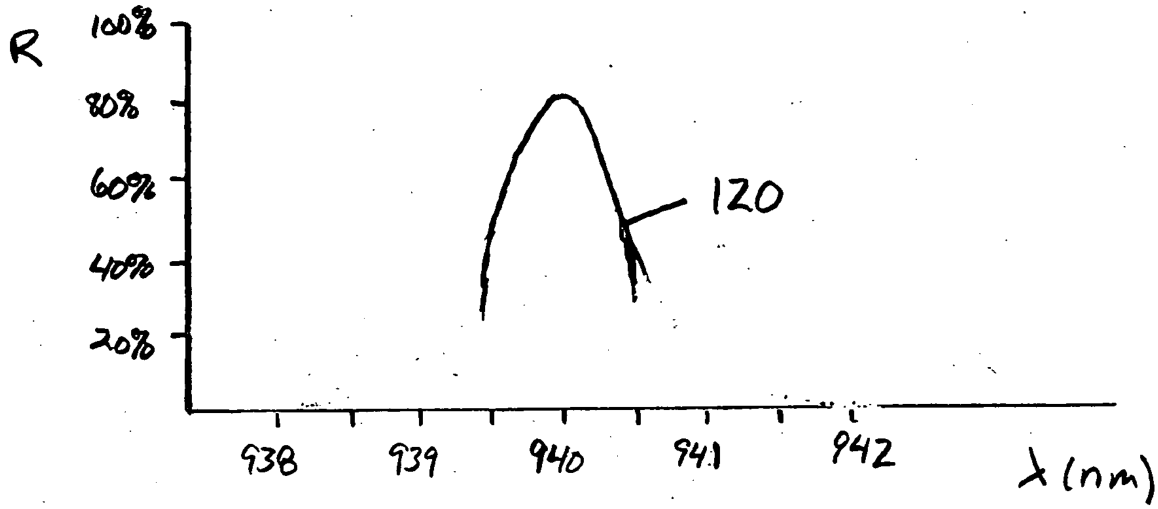

R
100%
80%
60%
40%
20%
120
938
939
940
941
942
λ (nm)

FIG. 6a

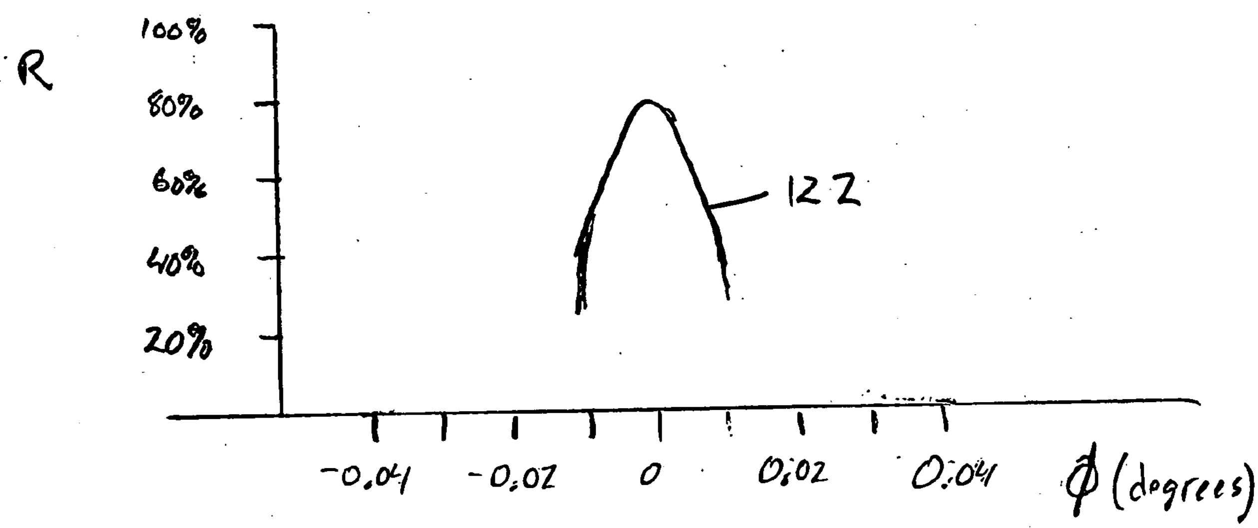

R
100%
80%
60%
40%
20%
122
-0.04
-0.02
0
0.02
0.04
φ (degrees)

FIG. 6b.

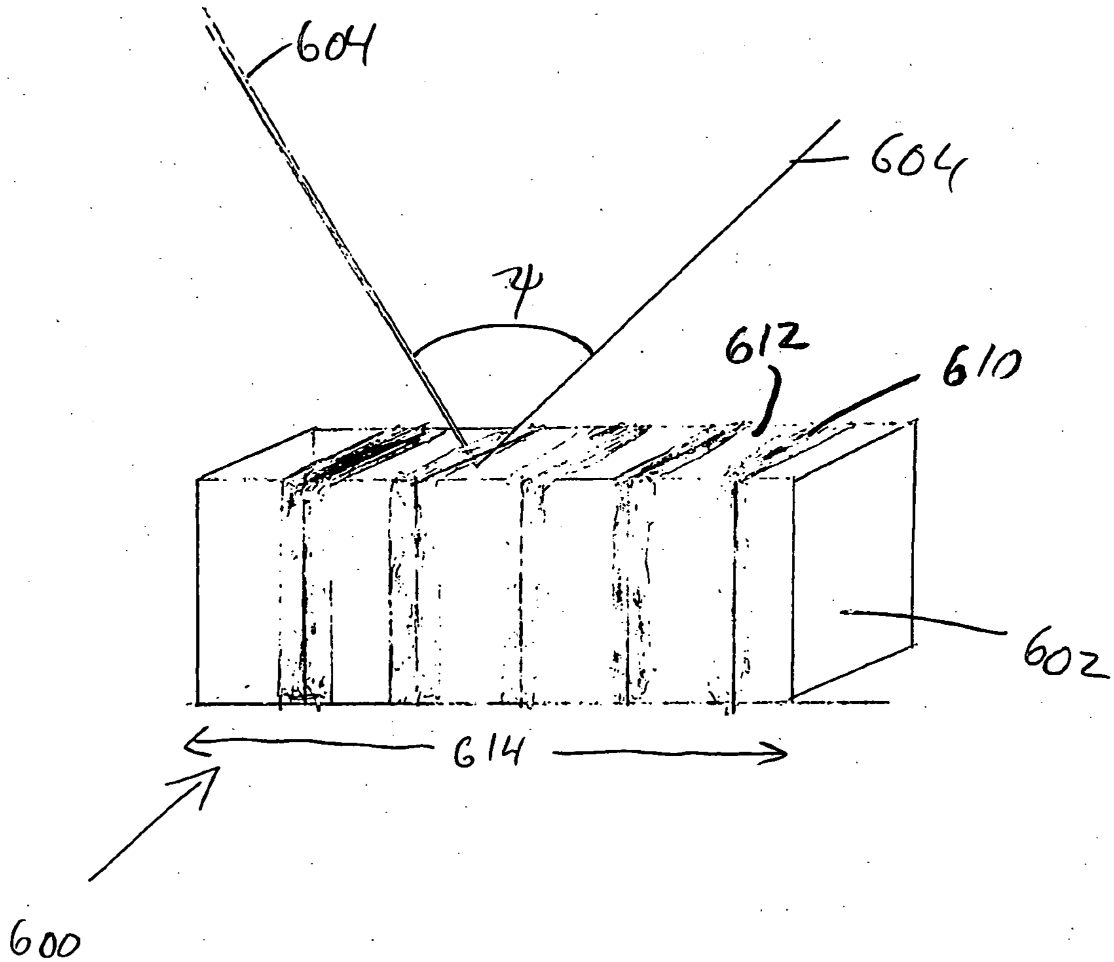


FIG 6c

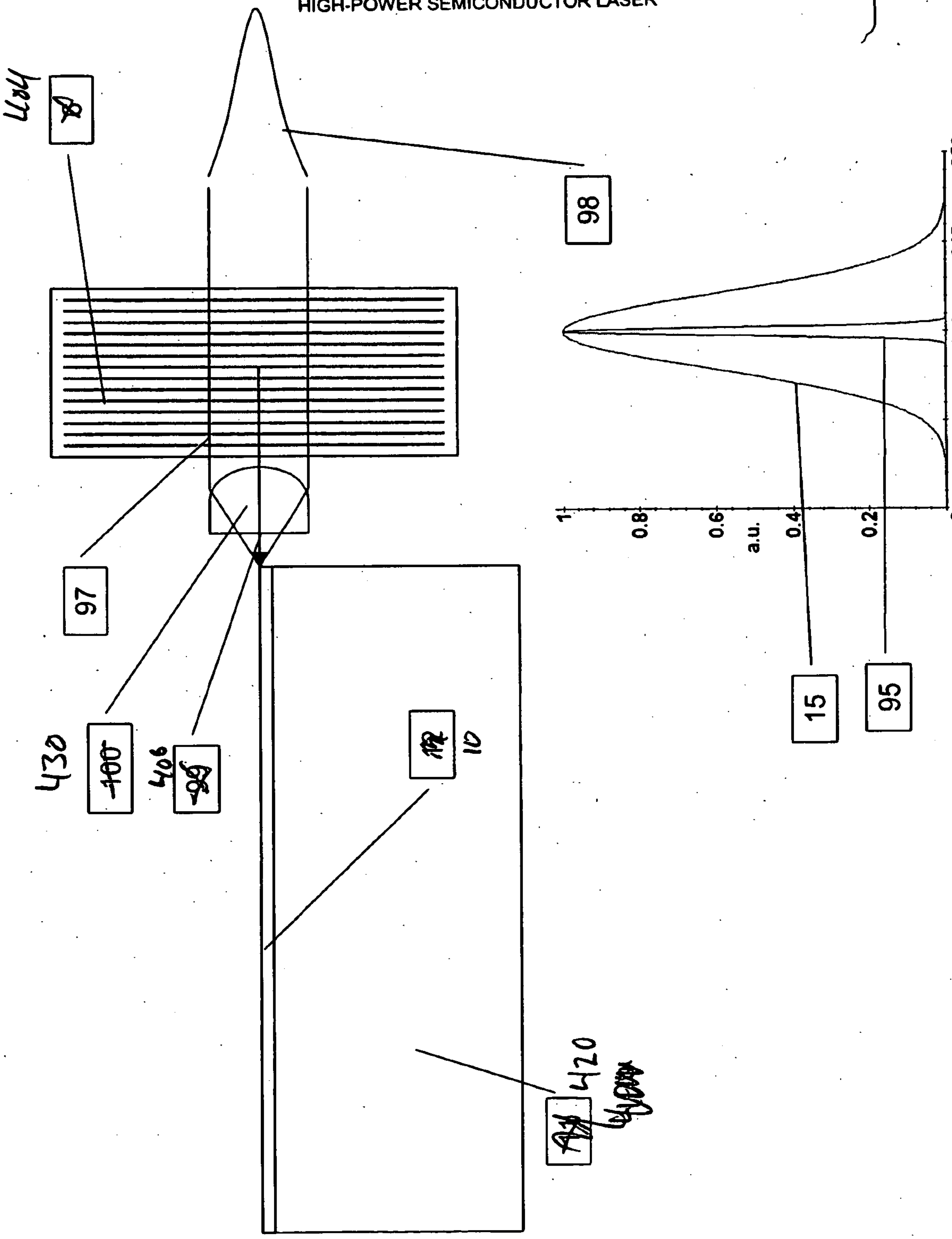


Fig. 7

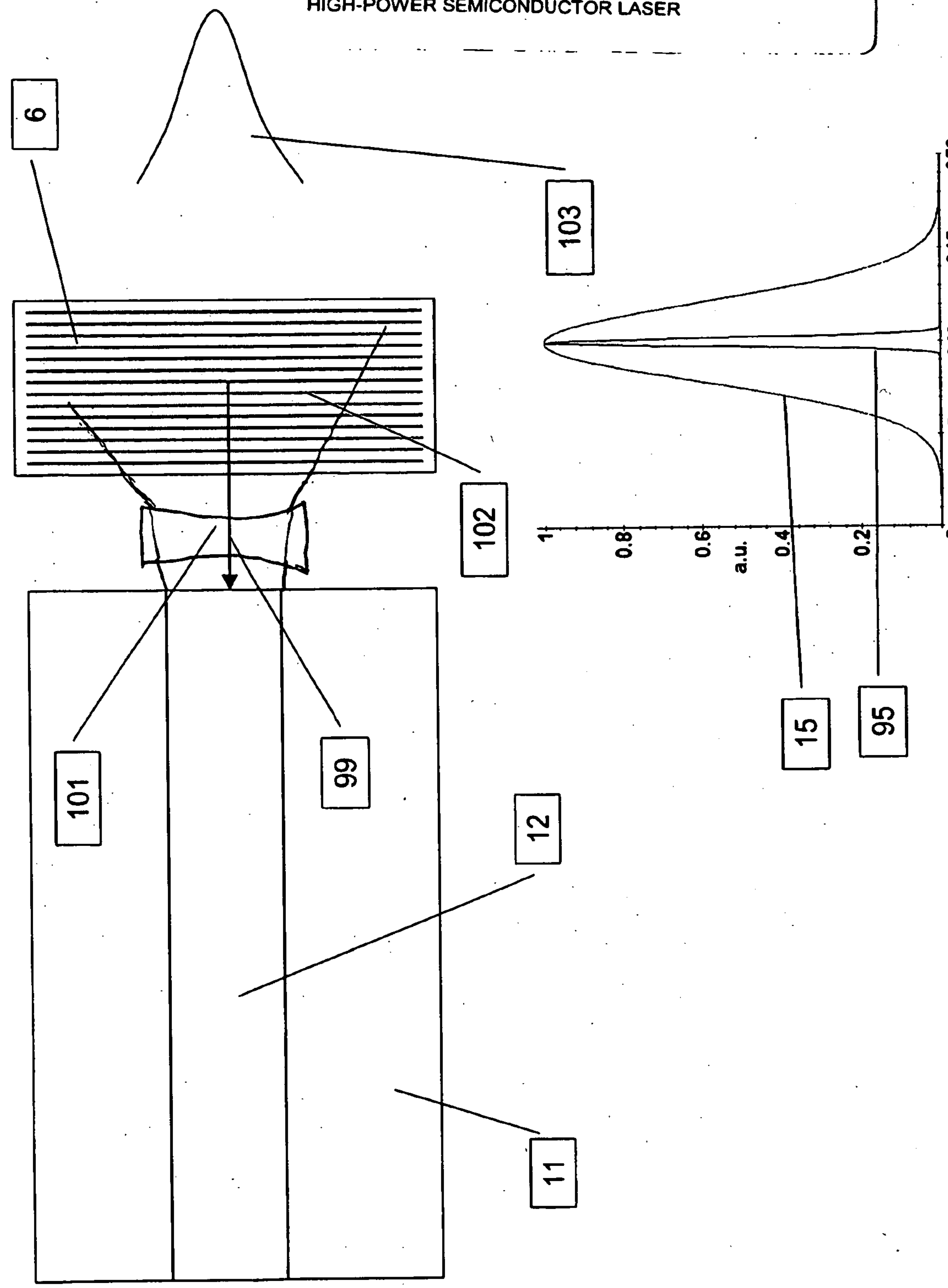


Fig. 8

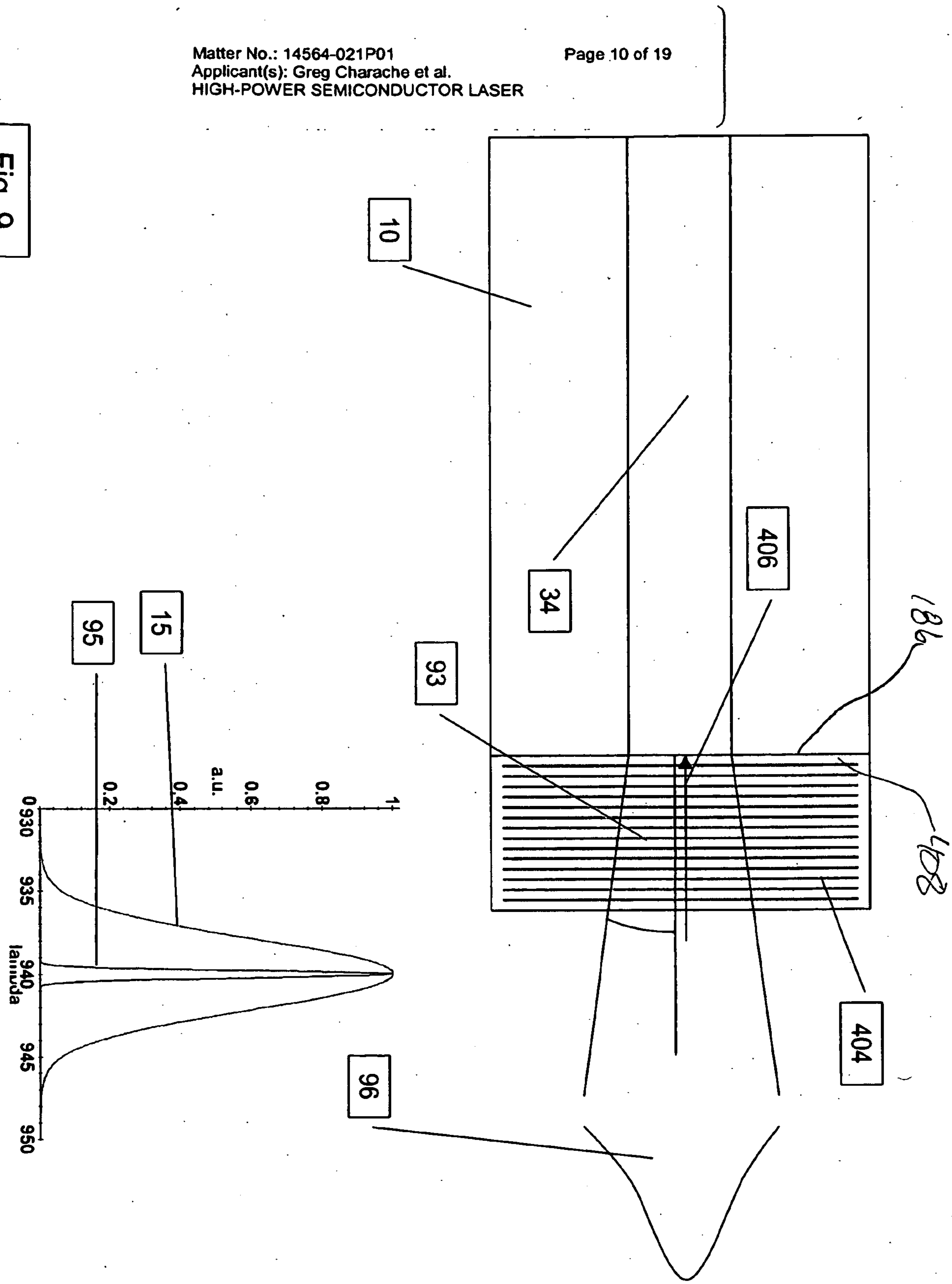
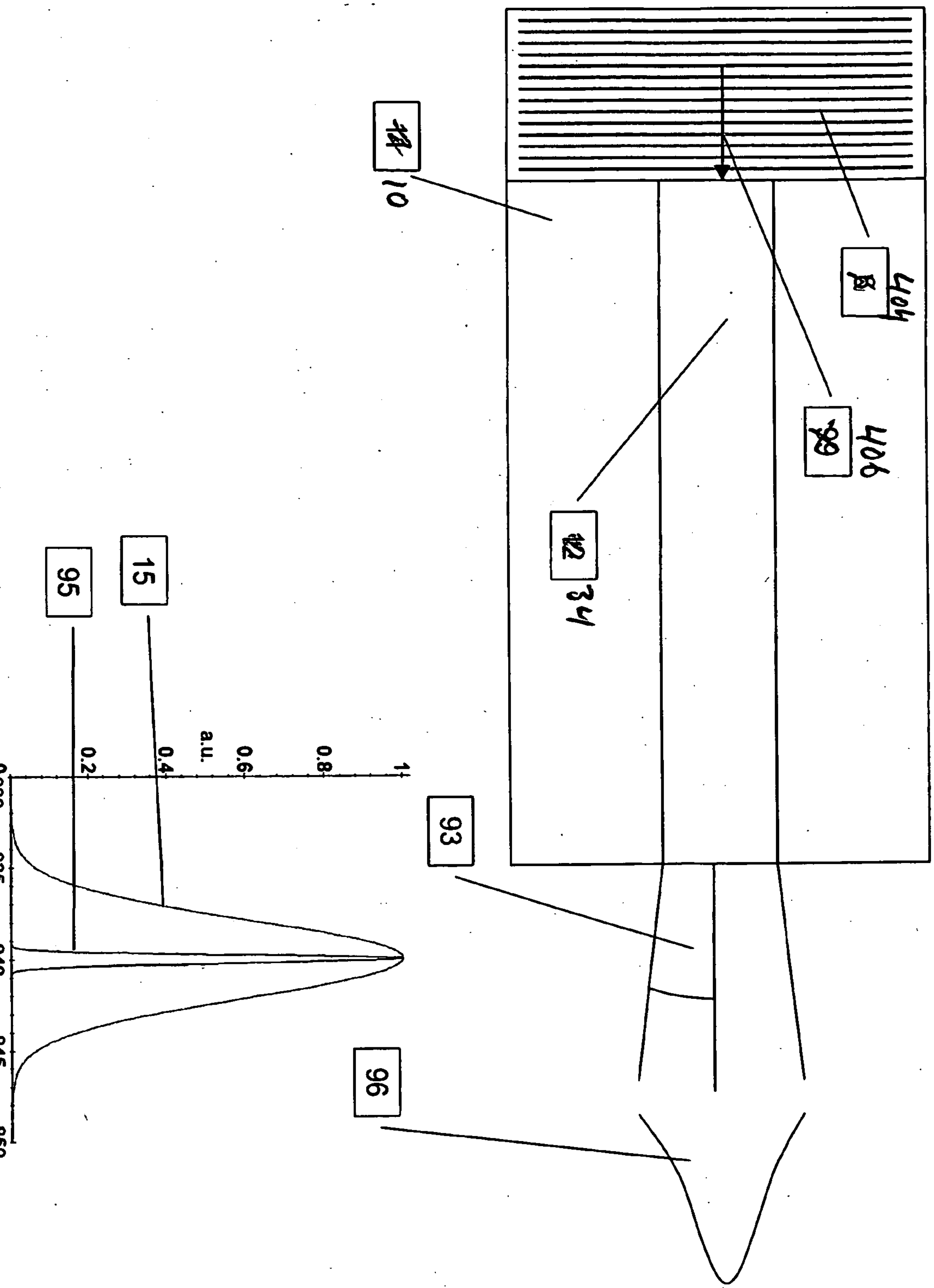

10
34
406
93
404
96
95
15
a.u.
0
0.2
0.4
0.6
0.8
1
930
935
940
945
950
lamda

Fig. 9

Fig. 10



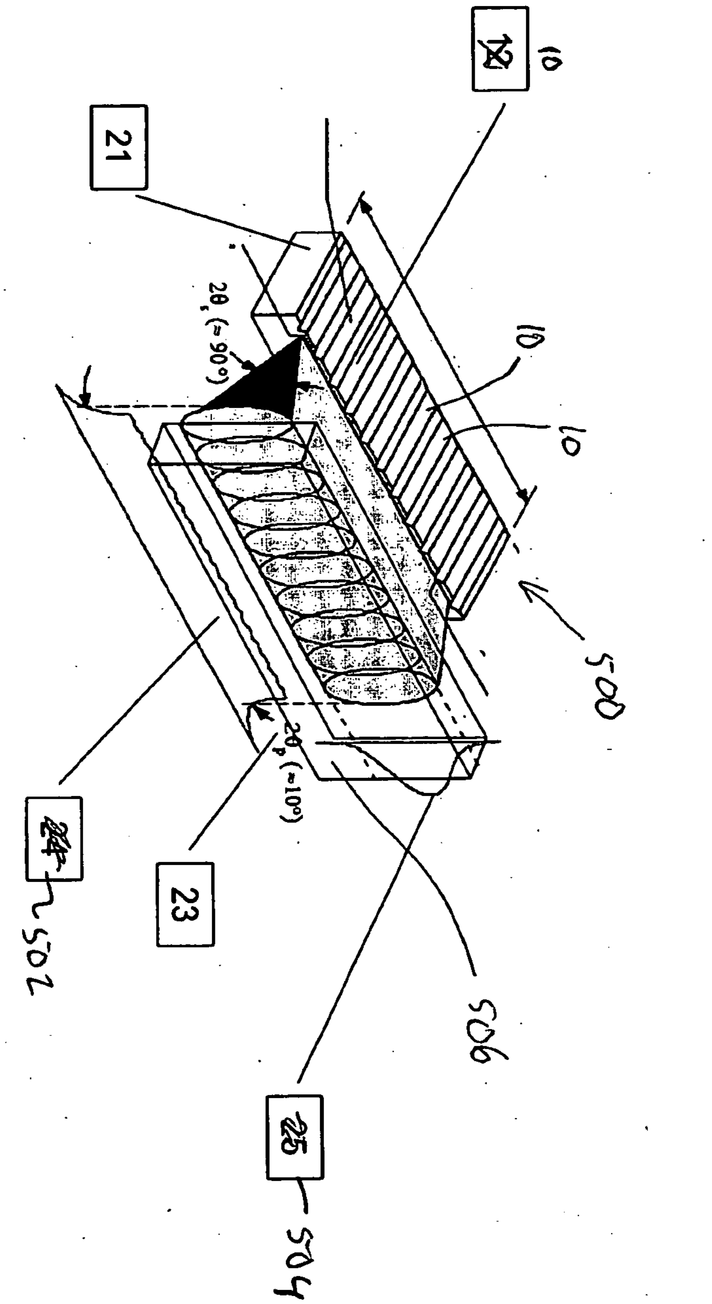


Fig. 11

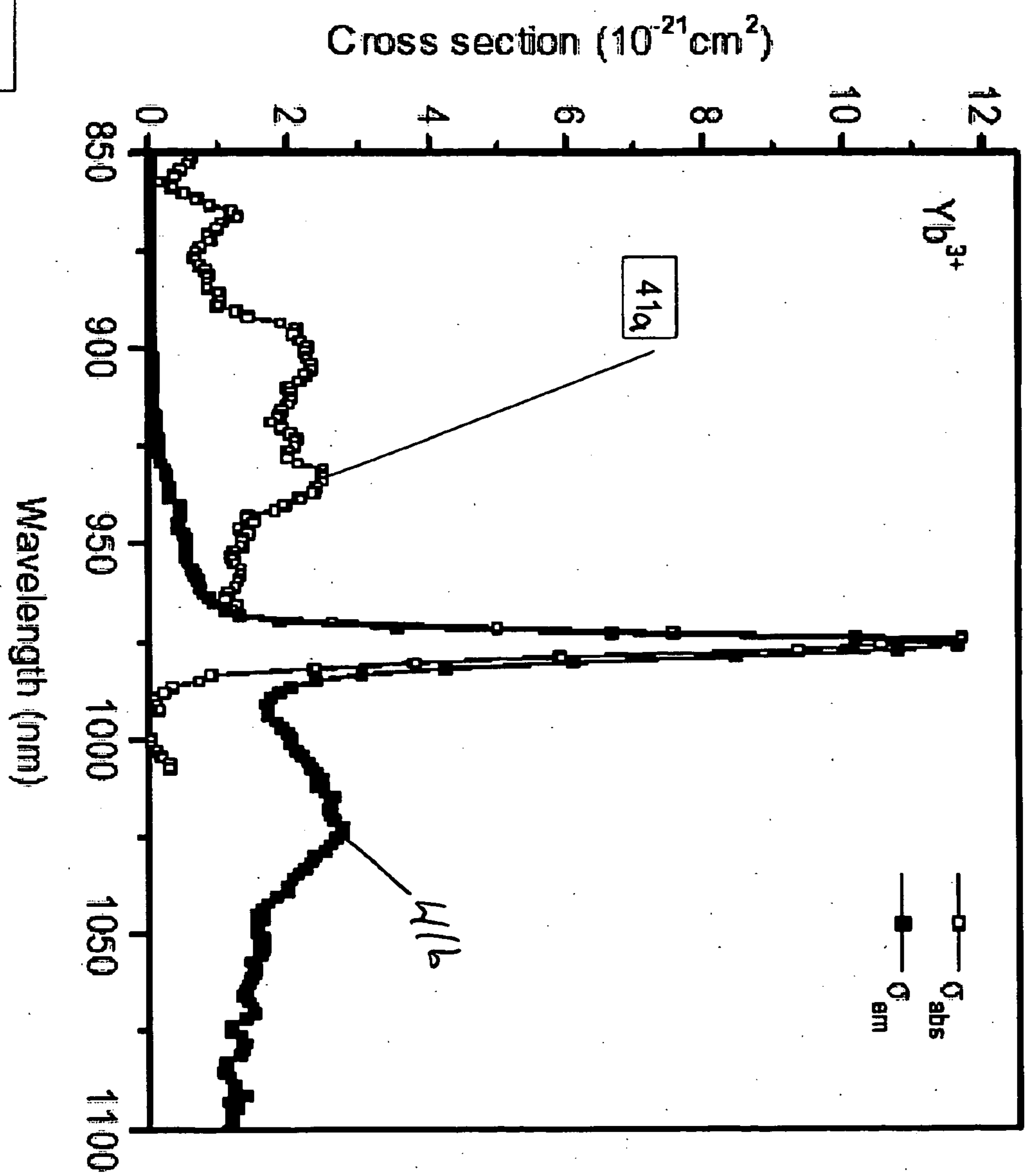

Cross section (10-21cm2)
0
2
4
6
8
10
12
850
900
950
1000
1050
1100
Wavelength (nm)
Yb3+
41a
41b
σabs
σem

Fig. 12

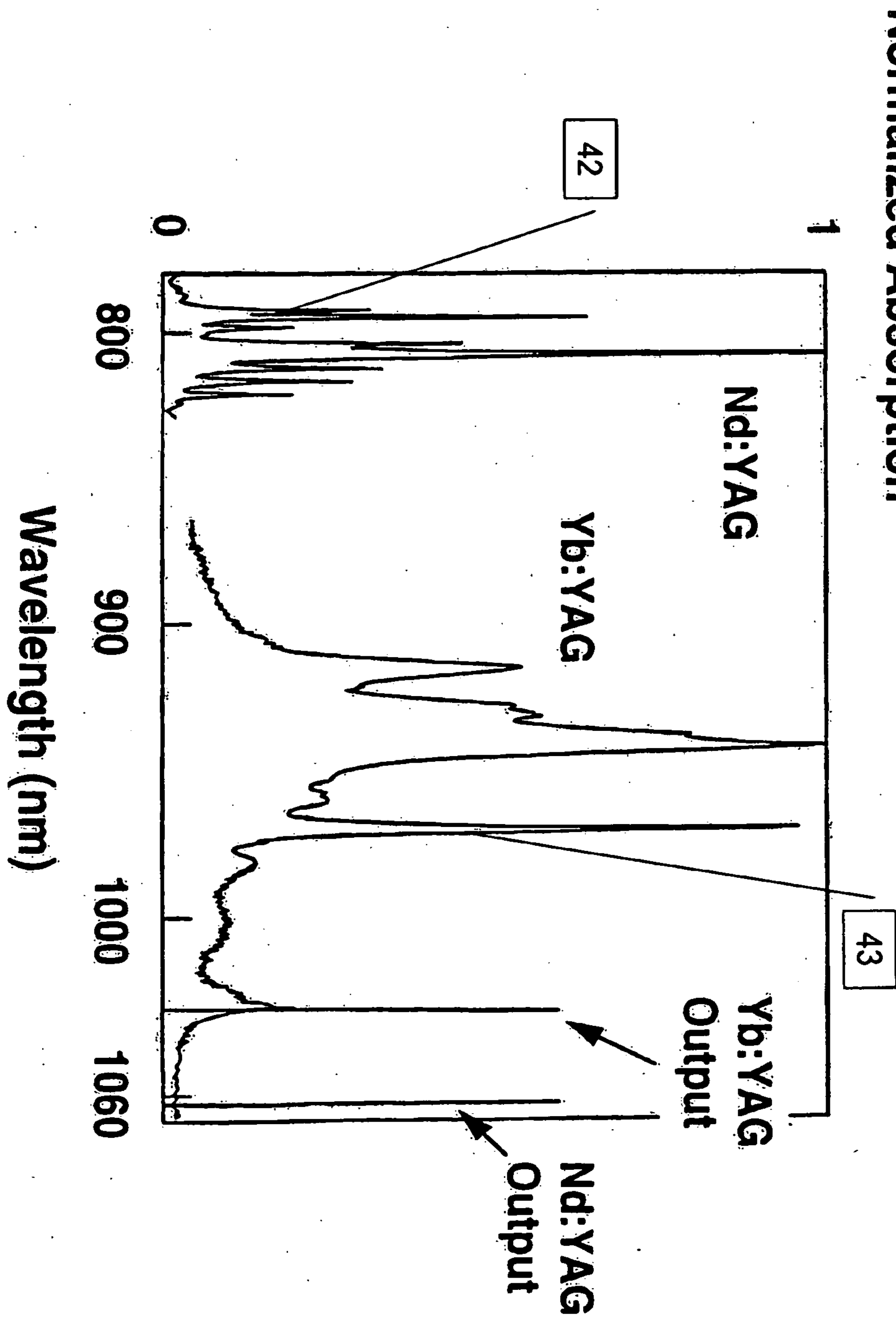

Normalized Absorption
1
0
800
900
1000
1060
Wavelength (nm)
Nd:YAG
Yb:YAG
42
43
Yb:YAG
Output
Nd:YAG
Output

Fig. 13

Fig. 14a

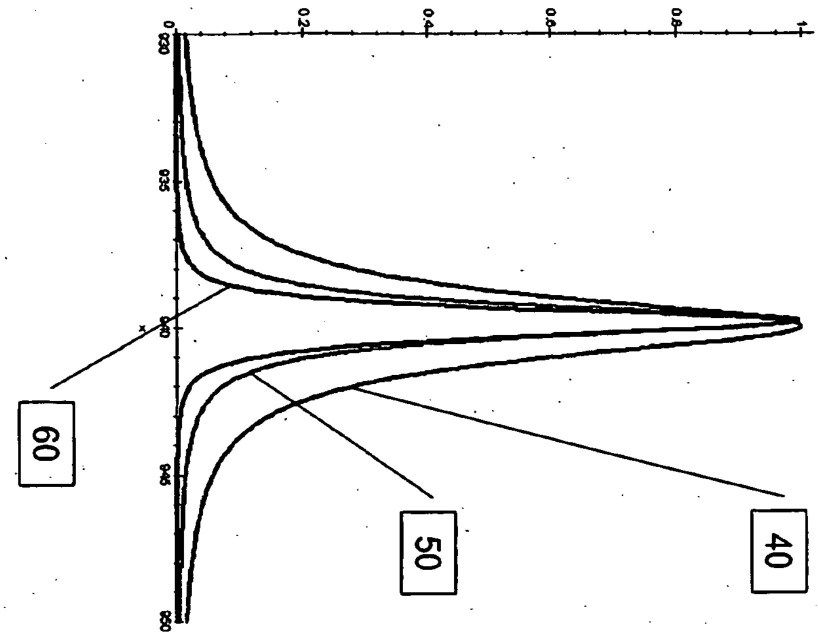
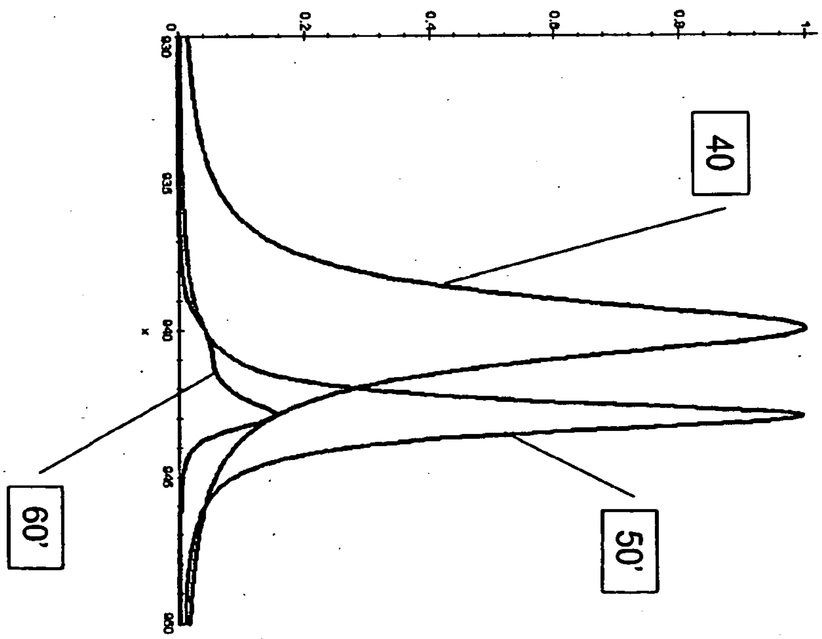


Fig. 14b



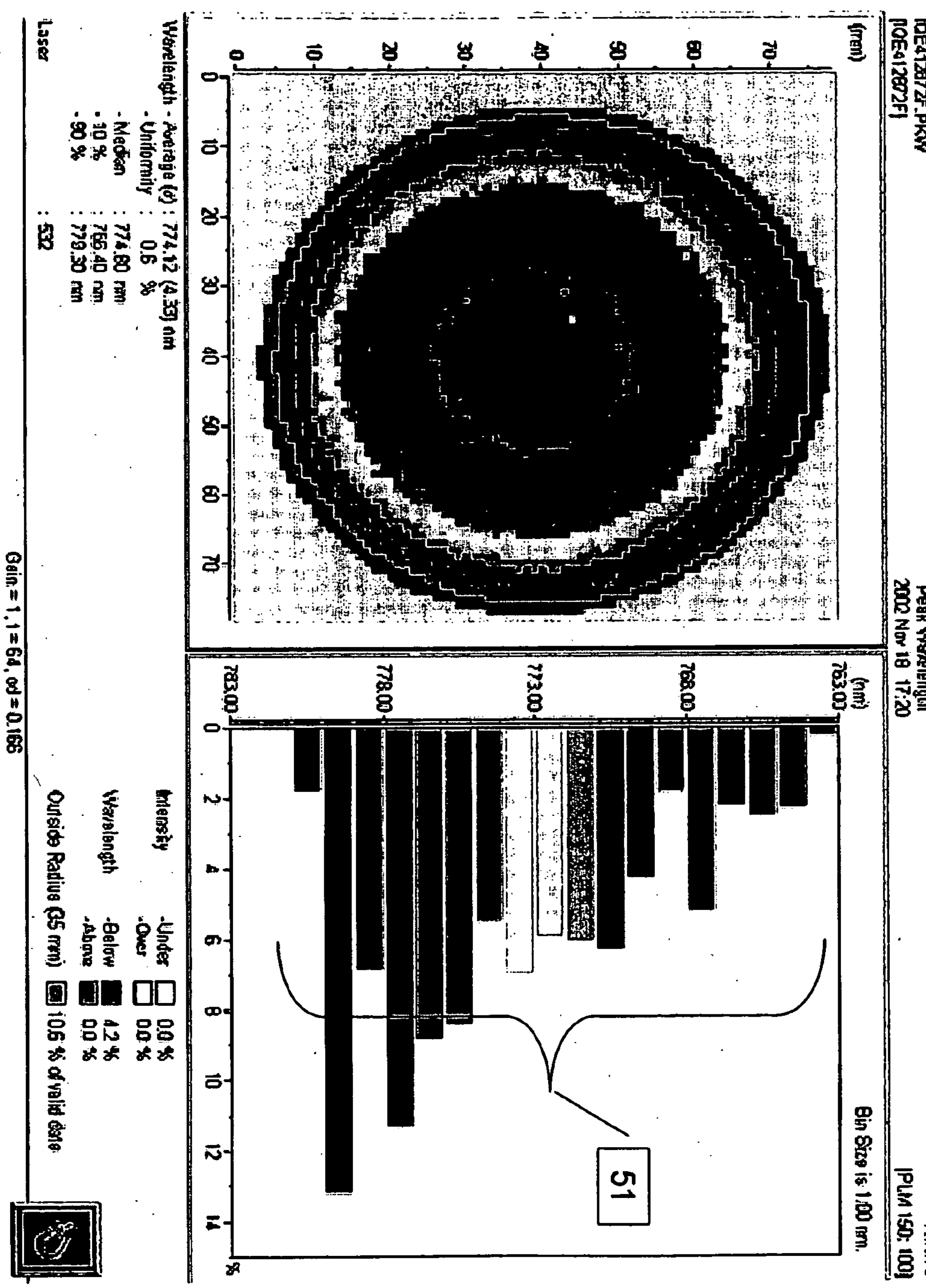

IOE41287ZF.PKW
[IOE41287ZF]
Peak Wavelength
2002 Nov 18 17:20
PHILIPS
[PLM 150: 100]
Bin Size is 1.00 nm.
(mm)
(nm)
51
Wavelength - Average (σ) : 774.12 (4.33) nm
- Uniformity : 0.6 %
- Median : 774.80 nm
- 10 % : 765.40 nm
- 90 % : 779.30 nm
Laser : 532
Gain = 1, t = 64, od = 0.166
Intensity -Under 0.0 %
-Over 0.0 %
Wavelength -Below 4.2 %
-Above 0.0 %
Outside Radius (35 mm) 10.6 % of valid data

Fig. 15

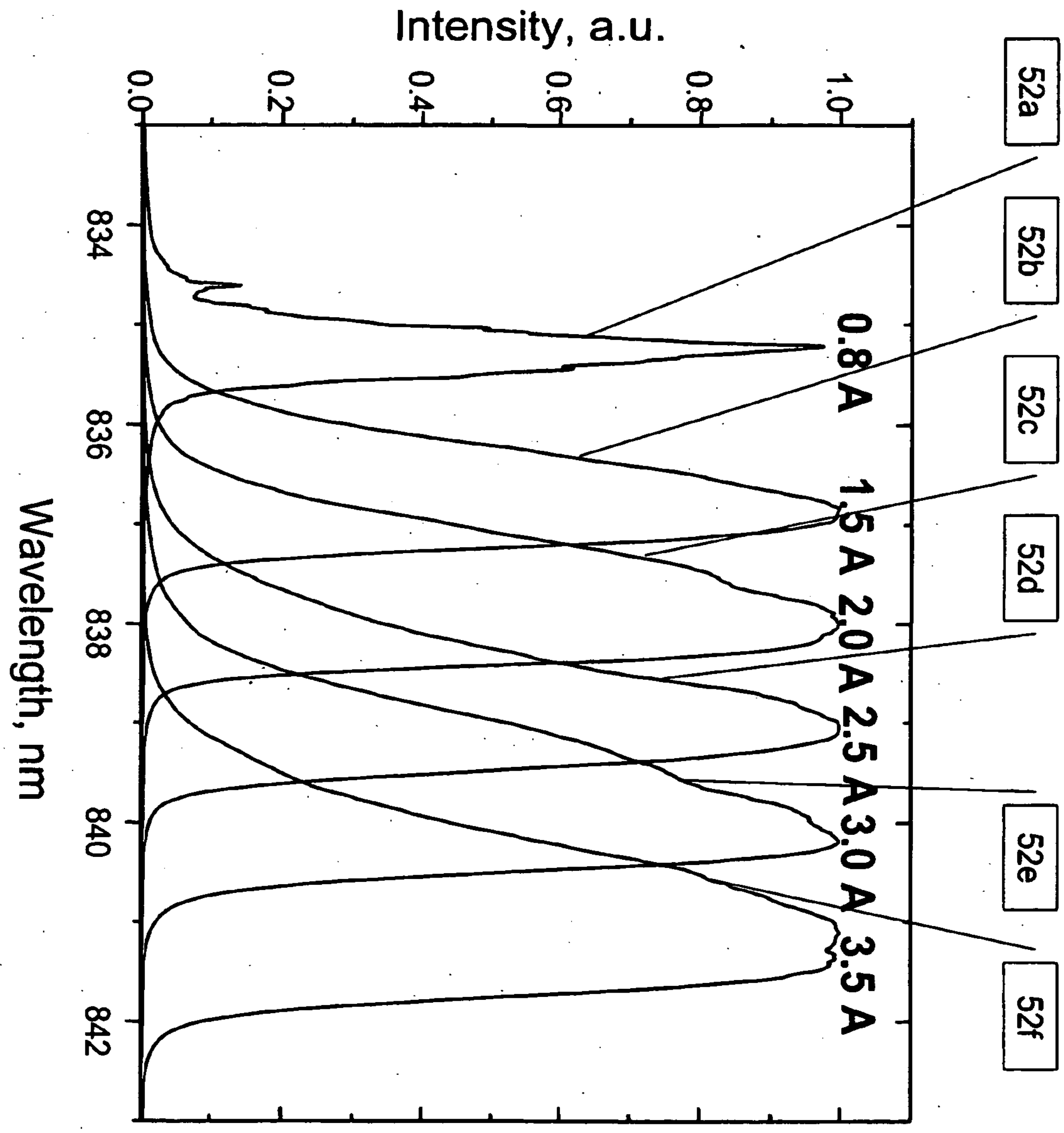
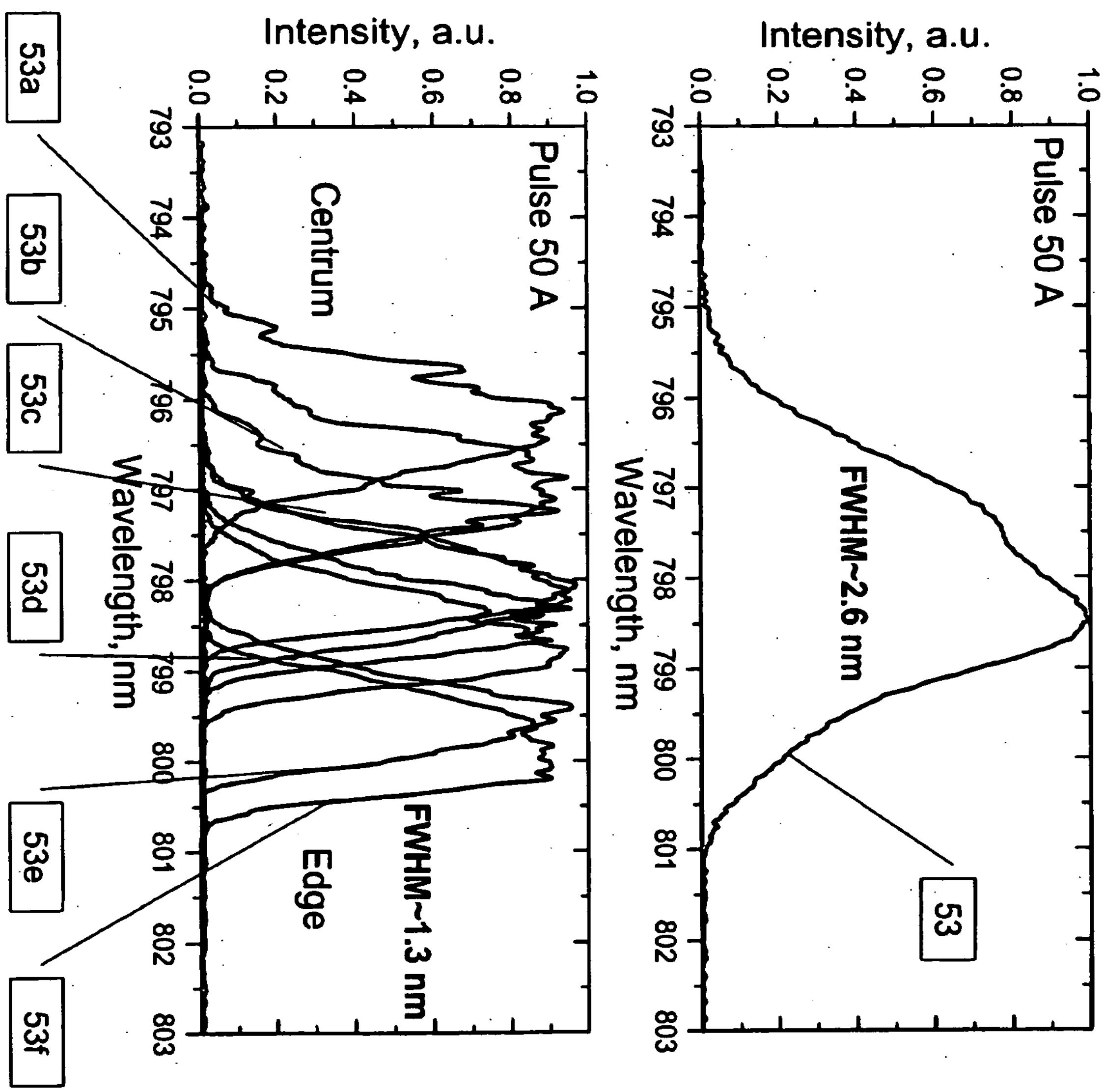

Intensity, a.u.
0.0
0.2
0.4
0.6
0.8
1.0
Wavelength, nm
834
836
838
840
842
0.8 A
1.5 A
2.0 A
2.5 A
3.0 A
3.5 A
52a
52b
52c
52d
52e
52f

Fig. 16

Fig. 17


Intensity, a.u.
0.0
0.2
0.4
0.6
0.8
1.0
Pulse 50 A
FWHM~2.6 nm
53
Wavelength, nm
793
794
795
796
797
798
799
800
801
802
803
Intensity, a.u.
Pulse 50 A
Centrum
Edge
FWHM~1.3 nm
Wavelength, nm
53a
53b
53c
53d
53e
53f

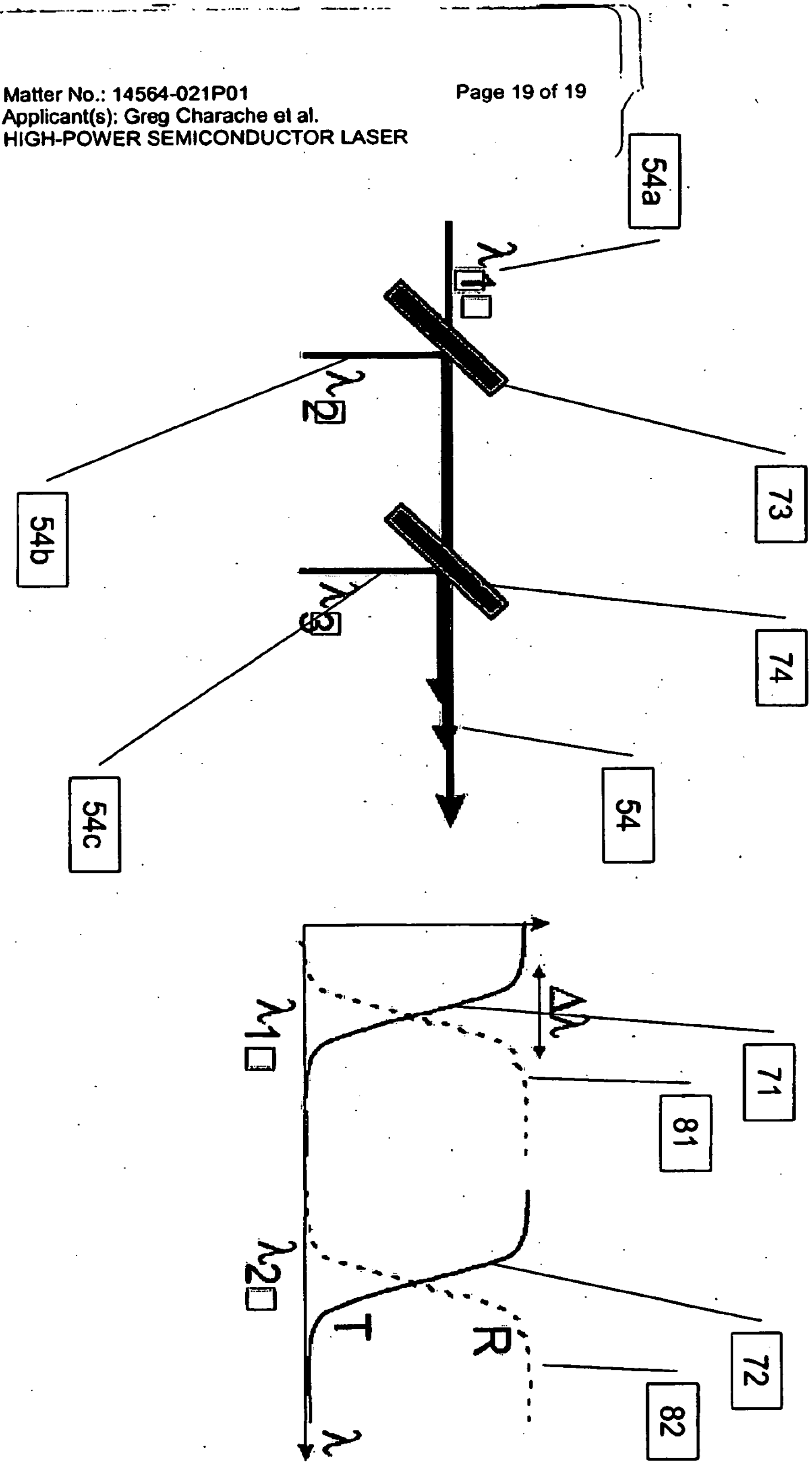


Fig. 18